Full length article

# Copper at the crossroads: Assessment of the interactions between low-carbon energy transition and supply limitations

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## ARTICLE INFO

## ABSTRACT

This article aims to assess the impact of copper availability on the energy transition and to determine whether copper could become critical due to the high copper content of low-carbon technologies compared to conventional technologies. In assessing copper availability through to 2050, we rely on our linear programming world energy-transport model, TIAM-IFPEN. We examine two climate scenarios (2 °C and 4 °C) with two mobility shape, implemented with a recycling chain. The penetration of low-carbon technologies in the transport and energy sectors (electric vehicles and low-carbon power generation technologies) is likely to significantly increase copper demand by 2050. To investigate how tension over copper resources can be reduced in the energy transition context, we consider two public policy drivers: sustainable mobility and recycling practices. Results show that in the most stringent scenario, the cumulative primary copper demand between 2010 and 2050 is found to be 89.4% of the copper resources known in 2010. They also pinpoint the importance of China and Chile in the future evolution of the copper market.

## 1. Introduction

The issue of mineral resource dependency is a relevant illustration of the challenges the world is likely to face in the energy transition process. Many studies (Alliance Nationale de Coordination de la Recherche pour l'Energie (ANCRE) 2015; World Bank 2017; OECD 2018) underline the need to take these constraints into account in the dynamics of the global energy transition, and especially the location of resources, the organization of industrial markets, and actors' strategies. As Kolotzek et al. (2018) pointed out, criticality assessments are intended to cover many dimensions of interest, which are usually vulnerability and supply risk based on economic concerns (Baldi et al., 2014a; Glöser et al., 2015), geopolitical concerns (the case of the rare earth elements (REE) production concentrated in China is a perfect illustration), geological or technical concerns (Harper et al., 2015a, b) sometimes extended to cope with environmental impacts (Graedel et al., 2012; Nassar et al., 2015a) or social implications (Bach et al., 2016, 2017). This can be even more complex as it can also depend on the scale of the analysis (i.e. the micro level (industrial

sector or enterprise), the macro level (countries) or the global level), on the chosen geographical scale (lithium is considered critical in the US but not in the European Commission's list of critical materials), on the time scale i.e. how long or short-term the assessment is made over (chromium was critical for the European Commission in 2014 but not in 2017) (Bonnet et al., 2019).

Whereas economic literature generally focuses on lithium (Kushnir and Sanden, 2012; Speirs et al., 2014; Hache et al., 2018; Hache et al., 2019a), cobalt (Helbig et al., 2018)and rare earths (Alonso et al., 2012a; Baldi et al., 2014b; Nassar et al., 2015b)to illustrate the systemic impacts of the energy transition on raw materials, this shift will also potentially impact the major non-ferrous metal markets (copper, nickel, zinc, etc.), as well as steel, cement, aggregates and water sectors (Hache et al., 2019b). Several economists and geologists have focused on copper, as evidenced by articles and responses by Tilton (2003a, b), Gordon et al. (2006), Tilton and Lagos (2007), Gordon et al. (2007) and more recently Vidal (2018a) on the subject of copper criticality. According to the International Copper Association (OECD 2019) around 35% of copper has been used for electrical power

& power utility in 2017 and this share could increase with the deployment of renewable energy technologies. In the context of the energy transition, and because copper is used in many applications in the transport and power sectors, this raw material appears to be an interesting case study on criticality issues. Therefore, it is necessary to integrate raw material supply chain in long-term energy models in order to take into account the supply limitations on resources for low-carbon technologies needed to shape future energy transition.

The current dearth of diversity in the raw material supply chain along with the rapid deployment of all decarbonisation and digital innovations required in the short to medium term, to meet more stringent environmental constraints and economic growth, raises concerns about the feasibility of meeting short-term roll-out targets (Ballinger et al., 2020). Since many important countries (such as China) are less and less interested in exporting strategic raw material and more and more constrained by their internal consumption (Wübbeke, 2013), many importing countries have considered resource supply limitations as a priority by formulating raw material strategies (Europe is a perfect illustration (European Commission, 2008, 2011, 2014, 2017). Raw materials supply risk and criticality have been widely discussed over the last two decades as said Hache et al. (2019a), although the concept of "raw material criticality" has been firstly introduced in 1939 by the US government for common defence, industrial demands, and military commitments within a geopolitical context to analyse uncertainty on relevant materials availability (U.S. Congress 1939). They found more than 2000 articles published on the issue of material criticality with nearly 80% of which since 2010. Moreover, an extensive part of the first literature was devoted to rare-earth elements (REEs) criticality, although in recent years an increasing number of metals have been studied.

With the multiple alternative pathways which are under studies to achieve the objectives of the Paris agreement, it is also necessary and valuable to assess the growing need for raw material in low-carbon technologies, as well as their impacts on the environment. Therefore, long-term energy analyses may not be relevant or may have to be re-evaluated if possible future constraints on material supply are not taken into account by energy modellers and policymakers.

According to the review literature, the existing approaches or methods related to the analysis of raw material demand could be gathered into two categories.

### 1.1. The first category of existing approaches or methods based on past analyses of raw material flows

On the one hand, the first category relies on the detailed analysis of past raw material flows to identify historical patterns or snapshot analysis within material flow analysis (MFA) or life cycle analysis (LCA) to quantify the environmental sustainability. Material flow analysis (MFA) is a common analytical tool to characterize material stocks and flows within national, regional, and global boundaries. At a city scale, Sörme et al. (2001) and Zhang et al. (2011) described and estimated the copper-in-use stocks in 1995 in Stockholm and in 2009 in Nanjing, respectively, while van Beers and Graedel (2007) conducted the same approach at Inner Sydney, Sydney Metro, all Australian states/territories, and Australia itself at the beginning of the century. At the contrary of a "snapshot" of a system in time as in previous articles, many authors have described the behaviour of a system over a time interval using the dynamic material flow analysis (D-MFA). It has been also used to estimate the amount of copper in-use stocks or scrap generation at different spatial scales. This approach has been conducted at a national and regional scales e.g. China (Hao et al., 2020; Soulier et al., 2018a; Zhang et al., 2014), North America (Gorman and Dzombak, 2020; Wang et al., 2018; Chen et al., 2016; Spatari et al., 2005), Europe (Soulier et al., 2018b; Bonnin et al., 2013), or at a global scale (Glöser et al., 2013a). A time-series Life Cycle Assessment (LCA) approach to examine the historical environmental impacts associated with

copper mining and smelting in the five largest Australian copper mines from 1940 to 2008 has been done by Memary et al. (2012). They explored the usefulness of LCA for assessing the impacts of the mining and minerals processing industry over 70 years by incorporating changes in ore grade and differences in technologies and regional energy sources. Song et al. (2017) and Jingjing et al. (2019) have conducted comparative analysis on copper based on LCA approach in Norway and China. The former assessed the environmental impacts of a Norwegian copper ore mine and identify significant environmental hotspots at the plant level, and then to compare the impacts of alternative energy and tailings management options in relation to the overall environmental performance of the mine. These studies have provided valuable information for scientific literature in exploring the historical patterns of the copper in-use stocks which is useful for extrapolating future stocks. They have been helpful to better understand copper supply chain and prepare long-term criticality mitigation strategies.

### 1.2. The second category of existing approaches or methods based on prospective analyses of raw material demand

On the other hand, the second category relies on prospective analyses of raw material demand i.e. the assessment of possible future growth of raw material along with energy transition. It could be subdivided into four main sub-categories.

The approach of the first sub-category is based on the analysis of possible future evolution considering past trends or assuming expected growth rates based on experts' opinion. Few decades ago, there have been studies on the long-term demand for copper, such as Fisher et al. (1972), Rohatgi and Weiss (1977) to estimate the future demand of copper in 1980 and 1990 using an econometric model. Schipper et al. (2018) employed and compared two methods to estimate future copper demand by 2100: a regression-based method where the future trend is extrapolated from the estimated relationship on the basis of empirical data from the past, and a stock-dynamics-based method which starts from the stock of applications, and calculates demand as a derivative. In the same vein, Halada et al. (2008) also developed a model of per capita correlations of the state of decoupling of various metals (e.g. copper) to estimated growth of so-called BRICs (Brazil, Russia, India, China) and the original G6 countries (Japan, USA, UK, France, Germany, Italy) to estimate the consumption of these metals until the year 2050. Elshkaki et al. (2016) also analysed the demand, supply, and energy implications related to copper production and use over the period 2010–2050 from the analysis of the historical demand for copper from 1980 to 2010 using regression analysis with per capita GDP, the level of urbanization, and time as explanatory variables. After modelling the dynamics of copper production with a prey-predator approach linking the evolution of reserves to that of industrial wealth, Vidal et al. (2019) simulated the future demand by 2200 based on assumed evolutions of world population and gross domestic product per capita. Through a dynamic material flow analysis, Zhang et al. (2015a, b) extrapolated future stock and demand of China by 2050 based on past patterns of the copper in-use stocks. Habib et al. (2016) analysed the geopolitical supply risk and the geographical transition trend of global primary production of REE in 86 different countries from 1994 to 2013, and further projected this transition in future i.e., 2050 by using the global distribution of current known geological reserves (2014) of metals as representative of their global primary production share by countries in 2050. On the contrary, in order to identify vulnerabilities for REE-consumers and to propose ways to address the environmental impacts of REE mining, Dutta et al. (2016) assessed the future of REE supply chains up to 2020 reflecting an anticipated growth in demand of 5%. Their assumption followed Roskill's estimates of global trends in supply and demand for rare earths found in Rollat et al. (2016), who also assumed a similar trend in forecasting demand for rare earths in Europe by 2020.

The second sub-category gathers studies which use prediction

models for exhaustible resource production such as bell-shaped curve-fitting models. amongst them, the Hubbert model and the generalized Weng model are the most influential, as they have been widely used in the field of exhaustible resource peak production prediction (Wang et al., 2017a). Wang et al. (2017a, 2015) used the Hubbert model and the generalized Weng model, respectively, to predict long-term rare earth production, although they only focused on China. Roper (2009) used empirical Hubbert-like functions for assessing copper, zinc and lead mining rates and estimated when the production would peak as also done by Laherrere (2010) for copper. On the other hand, Wang et al. (2020) analyse the global rare earth production in the long term using the Richards model which has similarities with the two previous models.

The two last sub-categories, in contrast, rely more on the assessment of future raw material demand using long-term energy models. In other words, the interaction can be seen as a multi-model, where a group of models co-evolve and interact with each another in a dynamic environment (Pauliuk et al., 2017). Indeed, the third sub-category is based on using the outputs from a long-term energy model or specific road mapping process as inputs into dynamic raw material demand assessment. Several studies have been done using this approach in line with the prospective scenario generated by energy system models or government's goals. Kuipers et al. (2018) conducted a Life Cycle Sustainability Assessment (LCSA) methodology for assessing potential environmental implications related to global copper demand scenarios by combining a life cycle approach with metal demand scenarios for the period 2010–2050. They considered the International Energy Agency (IEA) World Energy Outlook (2012) energy scenarios and incorporated them into the LCA model to account for developments in the background energy supply mix from 2010 to2050. Hertwich et al. (2015) developed an integrated hybrid LCA model to estimate the future copper requirements by 2050 of the wide-scale global deployment of different low-carbon electricity generation technologies as foreseen in the International Energy Agency's (IEA) BLUE Map scenarios (IEA, 2010). Likewise, McLellan et al. (2016) estimated the potential future copper production and potential for both secondary (recycling) and primary production expansion by defining extrapolated expansion rates of clean energy technologies from 2010 to 2050 from the analyses of IEA data. Their study just focused on three clean energy technologies (PV, wind and fuel cells), and not all available technologies. Kalvig and Machaceg (2018) assessed whether the global REE supply can keep pace with the REE demand for the expanding offshore wind energy sector through demand scenarios based on the estimates of GWEC up to 2030 while Imholte et al. (2018) did the same work by assessing the U.S. REE availability for supporting the U.S. wind energy growth targets based on annual U.S. wind installation targets up to 2030 established by the US Department of Energy. Other articles were more focused on raw material demand driven by future transport electrification or residential buildings. amongst them, Habib et al. (2020) estimated the future global demand of copper for passenger vehicles regarding growth of transport electrification which have been taken from three different scenarios run through the Integrated Model to Assess the Greenhouse Effect (IMAGE), while Deetman et al. (2020) and Marinova et al. (2020) focused on the in-use stock of raw material (Steel, Concrete, Wood, Copper, Aluminium, Glass) in residential and service buildings towards 2050 by translating material intensities per square metre into material stock using the total useful floor area specified for 26 world regions, as projected by the IMAGE model.

For the last and fourth sub-category where the raw material supply chain and LCI metrics have been integrated as inputs and constraints into prospective energy models, it has been noticed that fewer studies have been found in scientific literature. Some recent studies considered this approach; however, they were in majority covering rare-earth elements and their environmental implications, and few on other raw materials. Schandl et al. (2016) analysed whether well-designed policies can reduce global material and energy use, and carbon emissions,

with only minimal impacts on improvements in living standards. Their analysis are based on a novel modelling architecture employing a soft-link between three models as one: a top-down integrated climate and economy model (GIAM) (Gunasekara et al., 2008), a global, multi-regional technology-based physical stocks and flows model (MEFISTO) (Baynes et al., 2014), and a global multi-regional input–output model (Eora) (Lenzen et al., 2013). Alonso et al. (2012b) presented a top-down analysis of rare earth flows in order to identify the conditions where REEs may experience unprecedented demand growth, and assess the implications of co-mining on rare earth availability under rapid demand growth in specific industries. In particular, resource requirements for electric vehicles (EVs)[1] and wind turbines were estimated from performance specifications and vehicle sales or turbine deployment projections. Still, at a country level, Wang et al. (2017b) construct a computable general equilibrium (CGE) model to investigate the market impacts of environmental regulation on the production of rare earths in China. Likewise, Ge et al. (2016) constructed a dynamic computable general equilibrium (DCGE) model to forecast the production, domestic supply, and export of China's rare earths in 2025. These studies considered this approach, notwithstanding they were only top-down models. This type of models describes the interactions between different agents (e.g., households, producers, and the government), representing flows of goods and services in a market-based economy (Cao et al., 2019). The use of production functions and no explicit representation of the different technologies limit the detailed technological study. Moreover, technical progress is isolated from innovations in the energy sector. However, we can also pinpoint the work done by Northey et al. (2014) where they modelled mined copper production using the 'Geologic Resources Supply – Demand Model' (GeRS-DeMo) (Mohr, 2010). By listing all mines, including their ultimate recoverable resource and production and applying supply-demand parameters, GeRs-DeMo models the cumulative production over time (Mudd et al., 2012). Nevertheless, the authors pinpointed one of the limitations in applying this kind of supply focused model like the geRS-DeMo is their myopic insights into the future available options to meet the cu demand, and thus the need for coupling with material flow analysis. Currently to the best of our knowledge, no paper has been found in future raw material demand with an approach using a bottom-up long-term energy system optimization models. In this context, this article contributes filling the gap identified in the scientific literature on energy system optimization models by implementing raw material supply chain and material intensities of technologies in the different sectors of the economy in a bottom-up integrated assessment model. In this paper, we have developed the first bottom-up long-term energy model TIAM-IFPEN (TIMES[2] Integrated Assessment Model) with an endogenous copper supply chain from the resources to the end-use sectors, the availability constraints on resources and the trade balances. Given the recent attention given to concepts such as urban mining and recycling, this model could be helpful to provide unique insights in this area.

We present in this paper the main findings related to an endogenous representation of the copper supply chain in order to assess its dynamic criticality, along with technological changes through to 2050. It is crucial to understand whether the limited availability of copper can hinder the deployment of low-carbon technologies or conventional ones in the economy as a whole. This would be valuable for any energy analyses to examine the geological risk, geopolitical risk, production risk, etc. related to raw material supply availabilities and how they could impede the energy transition. In order to assess copper

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[1] Electric vehicles include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and fuel-cell electric vehicles (FCEVs). In this article, our transport module covers passenger light duty vehicles (PLDVs), Light, Medium and Heavy Commercial Vehicles (LCVs, MCVs and HCVs), Buses, Minibuses and two- and three-wheelers.

[2] The Integrated MARKAL-EFOM System.

availability through to 2050, two climate scenarios (2 °C and 4 °C) have been analysed with two different mobility scenarios each. Recycling has been also implemented into all these scenarios. The rest of the article is organized as follows. Section 2 describes the methodology, the overall structure of the TIAM-IFPEN model, and the specific features and assumptions considered for a detailed analysis of copper criticality. Section 3 presents our main results and related analyses on the copper supply chain at global and regional levels, copper resource availability and the implications of regionalized recycling policies and more sustainable road transport mobility. Finally, Section 4 summarizes the main conclusions.

## 2. Methodology

We have developed the first global bottom-up energy system optimization model with an endogenous representation of raw material supply chains in the TIAM-IFPEN (TIMES Integrated Assessment Model) model using a MARKAL[3]-TIMES framework (Fishbone et al., 1983; Loulou et al., 2004; Loulou et al., 2016) . TIAM-IFPEN is able to assess a dynamic raw material's criticality in a global energy prospective exercise subject to different climate and sectorial constraints through to 2050. However, contrary to our previous article (Hache et al., 2019a) based on assessing future risks related solely to the lithium supply chain with fast roll-out of electric vehicles in the coming years; we add a complete copper supply chain as an additional raw material constraint to the energy transition. The model will therefore allow analysing the dynamic criticality of copper through to 2050 based on current known resources, urban mining and resource availability.

### 2.1. Overview of the TIAM-IFPEN model

TIAM-IFPEN is a multiregional and intertemporal partial equilibrium model of the entire world energy system, based on the TIMES model generator (Loulou and Labriet, 2008). It is a version of the TIAM-WORLD developed, maintained and used by the Kanlo team and is the global incarnation of the TIMES generator. A complete description of the TIMES equations appears in the ETSAP[4] documentation. It is a bottom-up techno-economic model that estimates energy dynamics by minimizing the total discounted cost of the system over the selected multi-period time horizon through powerful linear programming optimizers. The components of the system cost are expressed on an annual basis while the constraints and variables are linked to a period. Special care is taken to precisely track cash flows related to process investments and dismantling in each year of the horizon. Different investment tracking cases have been considered in the model in order to help guarantee a smooth trajectory and a more realistic representation (Loulou and Labriet, 2008). The total cost is an aggregation of the total net present value of the stream of annual costs for each of the model's regions. It constitutes the objective function (Eq. 1) to be minimized by the model in its equilibrium computation. A detailed description of the objective function equations is provided in Part II, section 6.2 of the TIMES documentation (Loulou et al., 2016). We limit our description to giving general indications on the annual cost elements contained in the objective function:

– Investment costs incurred for processes;
– Fixed and variable annual costs,
– Costs incurred for exogenous imports and revenues from exogenous exports; however, in a global TIMES incarnation such as TIAM, exogenous imports and exogenous exports are not relevant;

– Delivery costs for required commodities consumed by processes;
– Taxes and subsidies associated with commodity flows and process activities or investments;

TIAM-IFPEN represents the global energy system divided into 16 regions[5] (See x in Appendix C). It is set up to explore the development of the world energy system from 2005 through to 2050 and is calibrated to the 2005 data provided by energy statistics of the International Energy Agency:

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} * ANNCOST(r, y)$$
(1)

**NPV** is the net present value of the total cost for all regions (the TIMES objective function);
**ANNCOST(r,y)** is the total annual cost in region *r* and year *y* (more details in section 6.2 of PART II (Loulou et al., 2016))
$d_{r,y}$ is the general discount rate;
**REFYR** is the reference year for discounting;
**YEARS** is the set of years for which there are costs, including all years in the horizon, plus past years (before the initial period) if costs have been defined for past investments, plus a number of years after EOH where some investment and dismantling costs are still being incurred, as well as Salvage Value; and
**R** is the set of regions in the area of study.

TIAM model is data driven, its parameterisation refers to technology characteristics, resource data, projections of energy service demands, policy measures etc. It means that the model varies according to the data inputs while providing results such as the shape of investments, technology pathways or the evolution of trade flows for policy recommendations (Hache et al., 2019a).

For each region, the model includes detailed descriptions of numerous technologies, logically interrelated in a Reference Energy System (Fig. 1) – the chain of processes that transform, transport, distribute and convert energy into services from primary resources and raw materials to the energy services needed by end-use sectors.

The model is driven by a set of demands for energy services in all sectors: agriculture, residential, commercial, industry and transport (Table 1). Each element in the network (Fig. 1) is characterized by several input parameters. The construction of the exogenous demands for energy services has been done via general equilibrium models such as the global General Equilibrium model GEM-E3[7] or GEMINI-E3,[8] which provide a set of coherent drivers for each region and for the World as a whole, such as population, households, GDP, sectors outputs, and technical progress. These drivers provided the growth rates for each demands for energy services through to 2050 following (Eq. 2):

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[5] The regions represent either individual countries, such as the People's Republic of China (China) or India, or aggregates of several countries, such as the Central and South America countries (CSA).

[6] The MoMo model is a techno-economic database spreadsheet and simulation model that enables detailed projections of transport activity based on user-defined policy scenarios through to 2100. The model covers 29 countries and regions with an urban/non-urban split, offering the potential for municipal-level policies to reduce transport energy use ((Fulton et al., 2009), https://www.iea.org/etp/etpmodel/transport/).

[7] GEM-E3 (General Equilibrum Model for Economy-Energy-Environment interactions) is a recursive dynamic computable general equilibrium model that covers the interactions between the economy, the energy system and the environment. (please refer to the GEM-E3 documentation for more details https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/gem-e3-model-documentation)

[8] GEMINI-E3 (General Equilibrium Model of International -National Interactions between Economy , Energy and the Environment) is a multi-country, multi-sector, recursive computable general equilibrium model

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[3] MARKet Allocation model.

[4] Energy Technology Systems Analysis Program. Created in 1976, it is one of the longest running Technology collaboration Programme of the International Energy Agency (IEA). https://iea-etsap.org/index.php/documentation
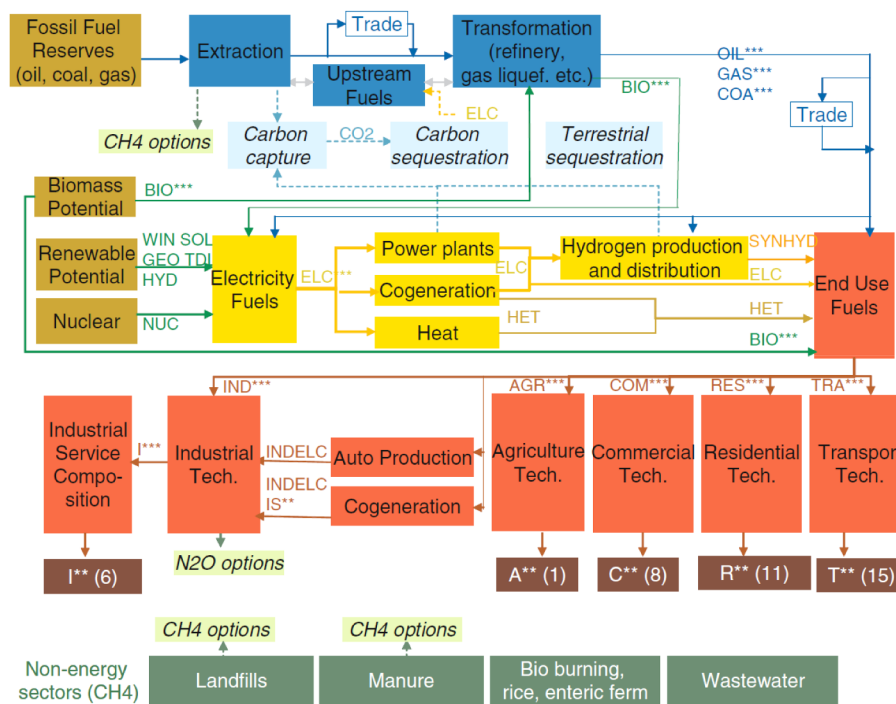
**Fig. 1.** TIAM model's reference energy system (Loulou and Labriet, 2008).

**Table 1**

Energy service demands and their drivers/input sources.[6]

| Demand | Driver | Via other model outputs |
|---|---|---|
| **Transportation** | **All regions** | **All regions** |
| PLDV | | IEA MoMo model |
| Bus and Minibus | | IEA MoMo model |
| Commercial vehicle travel | | IEA MoMo model |
| 2 & 3 wheelers | | IEA MoMo model |
| Rail passenger travel | POP | |
| Domestic aviation travel | GDP | |
| International Aviation travel | GDP | |
| Fret rail | GDP | |
| Domestic Navigation | GDP | |
| Bunkers | GDP | |
| **Residential** | **All regions after 2050 + Non-OECD before 2050** | **OECD regions before 2050** |
| Space heating | HOU | HOU |
| Space Cooling | HOU | GDPP |
| Water Heating | POP | POP |
| Lighting | GDPP | GDPP |
| Cooking | POP | POP |
| Regrigeration and Freezing | HOU | GDPP |
| Washers | HOU | GDPP |
| Dryers | HOU | GDPP |
| Dish washers | HOU | GDPP |
| Other appliances | GDPP | GDPP |
| Other | HOU | GDPP |
| **Commercial** | **All regions** | |
| Space heating | SPROD-Services | |
| Space Cooling | SPROD-Services | |
| Water Heating | SPROD-Services | |
| Lighting | SPROD-Services | |
| Cooking | SPROD-Services | |
| Refrigeration and Freezing | SPROD-Services | |
| Other electric demands | SPROD-Services | |
| Other | SPROD-Services | |
| **Agriculture** | **SPROD-Agriculture** | |
| **Industry** | **SPROD-X** | |

*Source:* (KanORS-EMR 2018)

PLDV: Passenger Light-duty vehicle; CV: Commercial vehicle; HOU: Households; POP: Population; GDP: Gross domestic product; GDPP: GDP per capita; SPROD-X: Industrial outputs of sector X

$$D_t = D_{t-1} * \left( 1 + \left( \frac{DRIVER_t}{DRIVER_{t-1}} - 1 \right) * decoupling\_factor \right) \tag{2}$$

The decoupling factors account for phenomena such as saturation (factor is then less than 1) and suppressed markets (factor is then larger than 1), and are in part empirically based. Most demands have economic growth as their driver.

Technologies are described by means of technical data (e.g., capacity, efficiency), environmental emission coefficients (e.g., CO2, CH4, N2O), and economic values (e.g., capital cost, date of commercialization). Possible future developments of the system are driven by reference demands for energy services (e.g. commercial lighting, residential space heating, air conditioning, mobility and many others), the supply curves of the resources (e.g., amount available at each price level), along with environmental or other constraints (e.g. greenhouse gas emission constraints, efficiency standards, energy portfolio, etc.), which are provided as exogenous inputs to the model (Fulton et al., 2009).

TIAM-IFPEN also includes a climate module which per se is directly inspired by the Nordhaus-Boyer model (Nordhaus and Boyer, 1999). It consists of three sets of equations, calculating the atmospheric concentrations of the three gases CO2, CH$_4$ and N$_2$O, the atmospheric radiative forcing of these three gases and of Kyoto GHG's that are not explicitly modelled in TIAM-WORLD (i.e. CFC's, HFC's, SF6), and finally the yearly change in mean global temperature. It includes two recursive formulas that calculate temperature changes in two layers (upper ocean + atmosphere layer, and lower ocean layer), as in Nordhaus and Boyer (Nordhaus and Boyer, 1999), recalibrated for TIAM-IFPEN and adapted to periods with variable length.

Although various recent studies have been already conducted using the TIAM model, such as the effects of global GHG reduction on bioenergy sector expansion (Kang et al., 2018) and carbon capture and storage in power supply (Selosse and Ricci, 2014) using TIAM-FR,[9] long-term investigation for large-scale low-GHG energy technology diffusion in Africa using TIAM-ECN[10] (Van der Zwaan et al., 2018), and the decarbonisation of road transport using TIAM-UCL[11] (Anandarajah et al., 2013), none has yet examined raw material supply chains in a TIAM model within energy transition analysis as far as we know.

### 2.2. Copper supply and demand modelling in TIAM-IFPEN model

#### 2.2.1. The copper supply chain

As explained by Gordon et al. (2007), copper is not uniformly distributed in the Earth's crust, as observed in the geographical distribution of copper ore reserves and resources (Fig. 2).

Nearly half of the world's reserves and resources are located in the CSA region (Central and South America), mainly in Chile and Peru. The copper supply chain has been implemented into the model from ore deposits to its end-use sectors via various transformation processes and trade flows (Fig. 3).

Regionalized mining CAPEX and OPEX have been done using weighted averages of real projects around the world ((Davenport et al., 2002; Boulamanti and Moya, 2016), companies' reports) (See Appendix B Table 11).

Two processes used for refining copper ores, pyrometallurgy and hydrometallurgy, have been implemented in the model. They concern ore concentrates and leached ores respectively. The regional disaggregation of these two refining processes is made using production weights since 1990, as displayed in Table 2. The shares of concentrates and leached ores have

been rather stable over time within a country between 2005 and 2015 due to the geological characteristics of the deposit.

As displayed in Fig. 4, copper is used in many sectors, such as the construction industry (plumbing, roofing, shipbuilding and cladding), the power sector (power plants and electrical infrastructures), the industry sector, the transport sector and in the final goods sector (the main component of coins for many countries, home accessories, water heaters, etc.).

"Electrical Networks", which include power distribution, lighting and earthing connection, are, alongside the "consumer sector",[12] by far the largest copper users as they consume respectively 34% and 31% of semi-finished copper products in 2017. These two sectors illustrate a general fact about copper: it is widely used in long-lived applications with useful life-spans that can last several decades. It is estimated that two thirds of the copper produced since 1900 was still in use in 2010 (Batker and Schmidt, 2015). Moreover, it appears that the "consumer" sector, pertaining to the manufacturing of final goods that are not related to transport, is the most dissipative end-use sector. A major barrier to the reuse of copper is therefore the long period during which it may be trapped in products that are still in use.

#### 2.2.2. The technology copper content

In a future driven by more stringent environmental constraints and economic growth, the increasing copper content of all decarbonisation innovations, particularly in the transport and power sectors, could, due to limited copper resource availability, hinder the diffusion of these technologies. The variability of technologies and their rapid evolution make it difficult to quantify the full requirements for energy raw materials (Table 3).

For some technologies such as nuclear, coal, gas and oil plants, the average copper content are almost identical between for example Ecoinvent and literature data (Hertwich et al., 2015, Vidal, 2018b). However, large discrepancies are observed for the RETs. According to Ecoinvent, copper content per unit capacity is ten times higher in a solar PV rooftop compared to a gas plant for example, while it triples in an onshore wind turbine compared to a nuclear power plant (Fig. 5). On the other hand, Vidal (2018b) assumed a copper content up to six times higher for an onshore wind compared to nuclear, while solar PV rooftop is only four times higher compared to a gas plant. In addition, concentrated solar plant (CSP) is for example not referenced in Ecoinvent while it could have different values for the same authors according to the year of publication. Vidal considered a copper content for CSP of 2.3 kt/GW in 2013 (Vidal et al., 2013) while it almost doubled in 2018 to reach 4 kt/GW (Vidal, 2018b). There are relatively few validated studies that give an exhaustive account of material intensities (in tonnes per unit of capacity), and most often they are limited to production infrastructure isolated from other equipment (transformers, connections, foundations, etc.) (Vidal, 2018a).

In this article, we have considered the copper contents which have been reported in Ecoinvent and we fill the missing technologies such as CSP with literature data (Fig. 5).

The same trend is observed in road transport vehicles. Compared to their inherent conventional vehicles, electric vehicles contain two to more than five times more copper (Fig. 6 and Table 4).

The copper content has been accounted for in each technology segment (Table 4).

Typically, between 96% and 100% of the copper is in the vehicle (for wiring), while in electric vehicles, the copper in the latter falls to 45% due to the much heavier battery, which contains 55% of the copper (Vidal, 2018b). More emphasis will therefore be placed on the

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[9] TIAM-FR is a version of TIAM adapted at the Mines ParisTech Centre of Applied Mathematics in Sophia-Antipolis (France).

[10] TIAM-ECN is the version of TIAM developed at the Energy Research Centre of the Netherlands (ECN).

[11] This version of TIAM was developed at University College London (UCL) through the UK Energy Research Centre (UKERC).

[12] This includes consumer and general products (appliances, instruments, tools and other), cooling (air conditioning and refrigeration), electronics (industrial/commercial electronics and PCs) and miscellaneous items (ammunition, clothing, coins, etc.).
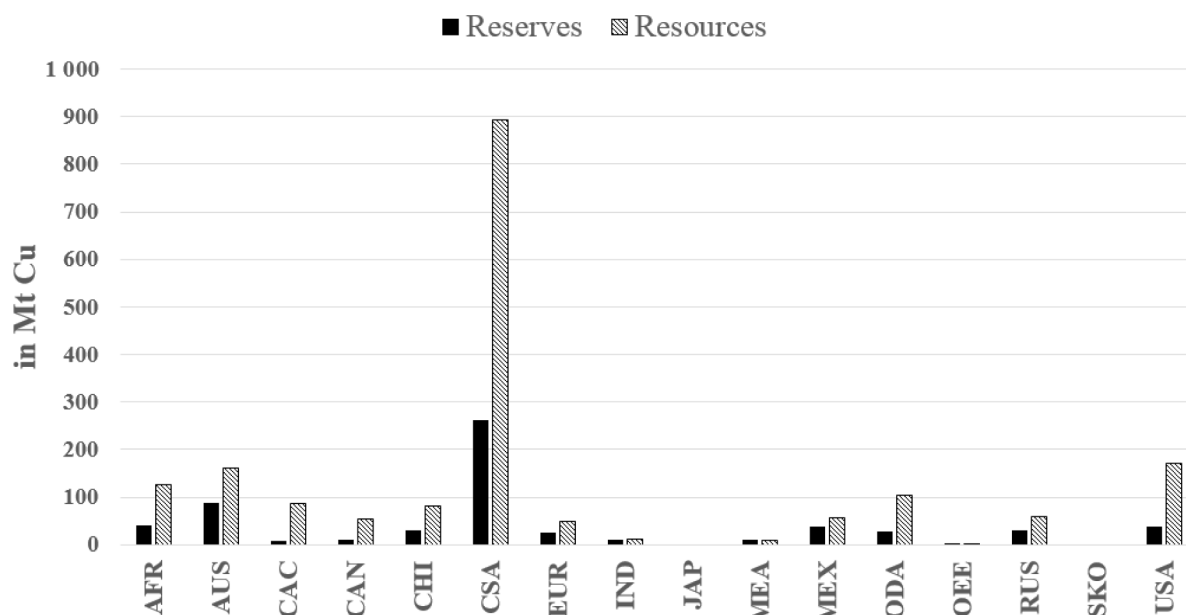
**Fig. 2.** Geographical distribution of copper resources and reserves worldwide.
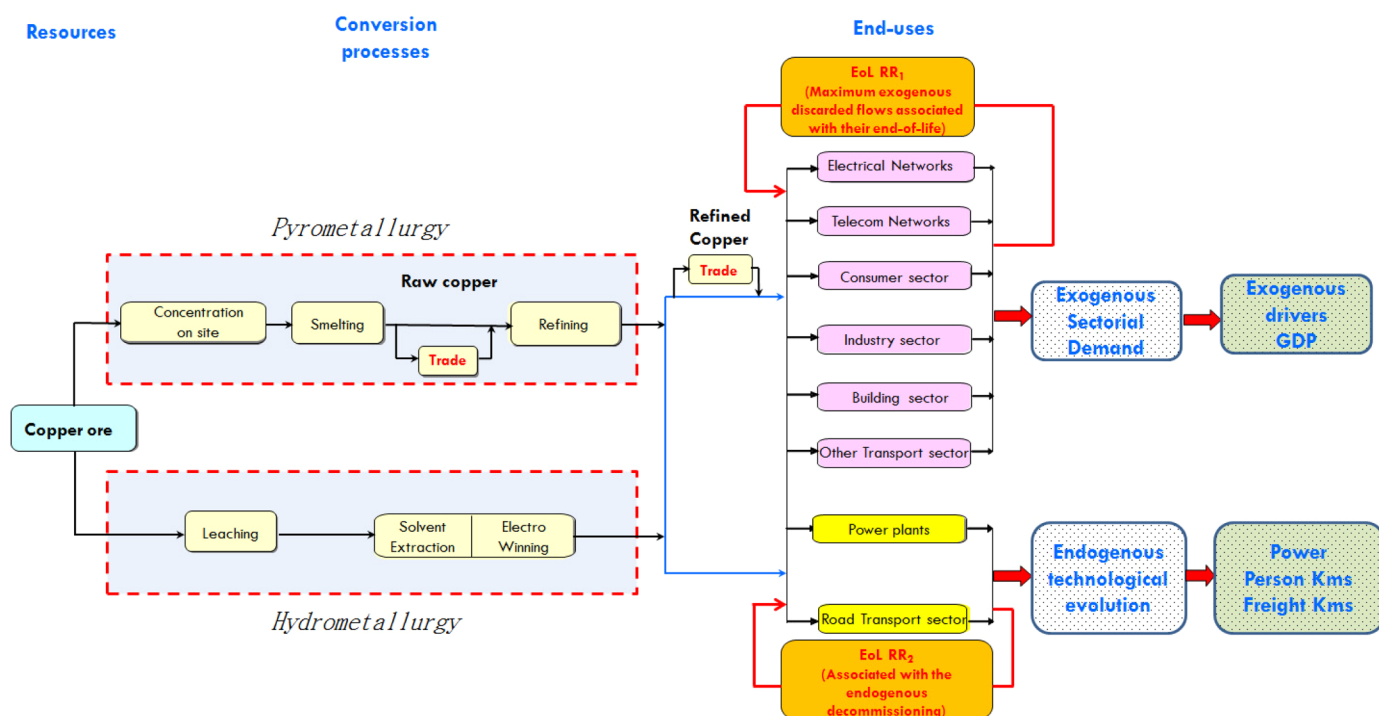*Source*: USGS, (Habib et al., 2016; Mudd et al., 2013)



**Fig. 3.** Detailed description of the copper supply chain in each TIAM region.

**Table 2**
Average share of ore concentrates (pyrometallurgy) in cumulative mine production (in%) over the period 2005–2015 in the main producer countries.

|      | AFR | AUS | CAC | CAN | CHI | CSA | EUR | IND | JAP | MEA | MEX | ODA | OEE | RUS | SKO | USA |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **Pyro** | 65 | 96 | 95 | 100 | 98 | 71 | 92 | 100 | 100 | 95 | 73 | 89 | 94 | 100 | 100 | 59 |

*Source:: USGS*

need to increase the recycling efficiency of copper from scrap in all end-use economic sectors.

Copper is traded in three forms worldwide. The first is the copper concentrate which have been processed by pyrometallurgy techniques. The second is refined copper cathodes, sold by copper refineries. This is the purest form of copper and is used to produce wires, sheets and strips,
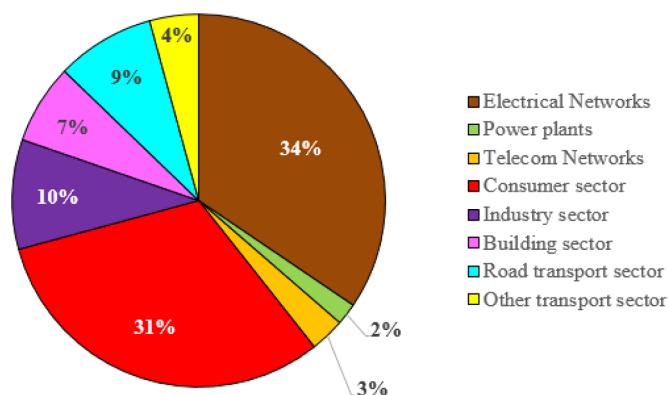
**Fig. 4.** End-use consumption of copper worldwide in 2018.
*Source*: (International Wrought Copper Council/ International Copper Association, 2019)

**Table 3**
Variation of the copper content for power generation technologies in the literature.

| Copper content (kt/GW) | Literature data | |
|---|---|---|
| | Min. | Max. |
| Gas | 0.5 | 1.5 |
| Nuclear | 0.06 | 1.5 |
| Oil | 1.5 | 1.5 |
| Coal | 0.3 | 2 |
| Wind onshore | 1.6 | 20.1 |
| Wind offshore | 0.9 | 11.7 |
| Solar PV (Rooftop) | 0.02 | 11.4 |
| Solar PV (Ground) | 3 | 7.5 |
| CSP | 0.4 | 12.4 |
| Hydro. | 0.1 | 11.4 |
| Run-of-river | 3.5 | 4 |
| Geothermal | 0 | 0.5 |
| Biomass | 0 | 0 |

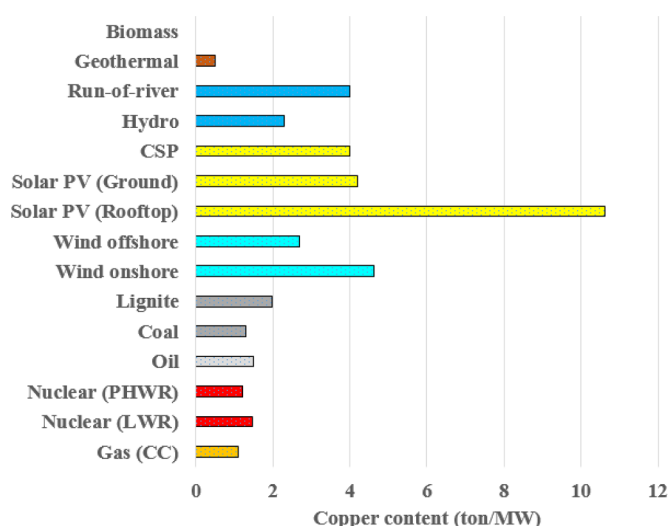*Source:* (World Bank 2017; O. Vidal, 2018)



**Fig. 5.** Copper content of different means of energy production (kg/MW) considered in the model TIAM-IFPEN.
*Source*: **Ecoinvent.**
**CC: Combined Cycle; LWR: Light Water reactor which encompasses the PWR (pressurized water reactor), the boiling water reactor (BWR), PHWR: Pressurized heavy Water Reactor; PV: Photovoltaic; CSP: Concentrated Solar Plant**

for example. The last traded product is blister copper. Custom refineries process blister copper to produce cathode; however, this represents a small share of the global copper trade. So, for simplification's sake, we consider two types of trade in the model. In Fig. 3, the first is trade in raw copper, encompassing all trade in copper ores and concentrates, copper mattes, copper anodes and unrefined copper. The second is refined copper. Taking into account trade capabilities enables analysis of future international copper trade and strategies based on each region's needs and growth. This use of the model would be very relevant, as historical trade analysis pinpoints changes in regions' strategies in response to environmental and economic constraints between 2005 and 2015 (see the example of China in Appendix A). Trade data were extracted from the resourcetrade.earth website, which uses the UN Comtrade database as a primary source and corrects missing points.

### 2.2.3. The recovery and recycling of copper in the TIAM-IFPEN model

Strong growth in emerging economies over the past decade, together with the rapid deployment of innovative copper-intensive technologies, has led to a sharp increase in copper demand. The recovery and recycling of copper helps to satisfy this demand and to build a sustainable future.

Glöser et al. (2013b) discussed several commonly used indicators to measure it at the global level. In this paper, we implement the End-of-Life Recycling Rate (EoL-RR) indicator in our TIAM-IFPEN model in order to take into account the efficiency of scrap recycling. This indicator is determined as the fraction of metal contained in end-of-life products that is collected, pre-treated and ultimately recycled back in the anthropogenic cycle (Eurométaux and Eurofer 2012 cited in Tercero Espinoza and Soulier, 2018).

There is a lack of data on recycling activity in copper-consuming sectors, but Glöser et al. (2013b) provided global estimates for the 2000–2010 period. The EoL-RR value for the eight copper-consuming sectors considered in the model is presented in Fig. 7. The average value for all sectors combined is around 45%. In each end-use sector, different lifetime distributions have been implemented in order to take into account their end-of-life. Estimated mean average lifetime values have been extracted from Glöser et al. (2013b) and are shown in Fig. 8, for the lifetimes of power plants and road transport, we relied on the IEA-ETSAP and IFPEN databases.

For the copper-consuming sectors not represented in detail technologically, i.e. the sectors in pink boxes shown before in Fig. 3, the estimated EoL-RR$_1$ will allow calculating exogenously the maximum discarded flows which could be recycled according to the historical data and the mean average lifetimes considered in the model. For the road transport and power sectors in yellow in Fig. 3 which have a detailed technological representation, the EoL-RR$_2$ value is provided and the model will calculate endogenously the maximum discarded flows associated with their inherent technology decommissioning. Given the lack of scalable EoL-RR data, we make a conservative hypothesis, assuming they are kept constant in the model over our 2005–2050 time horizon periods. This is a pessimistic scenario considering that significant efforts would certainly be made to improve copper recycling, such as in the "consumer sector", due to its dissipative characteristics and weight in copper consumption. In other words, the sectorial EoL-RR implemented in the model provides the basis of our pessimistic view of recycling activity (probable minimum values).

### 2.3. Macro-economic assumptions and scenario specifications

#### 2.3.1. GDP and population scenarios

The GDP per capita evolution has been derived from the assumed evolutions of population and GDP (Fig. 9). The UN released a revision in 2019 of the foreseen growth of all countries in the world (United Nations (UN), Department of Economic and Social Affairs, Population Division 2019). The world population has increased from 7.4 billion to around 9.7 billion inhabitants in 2050 in the median
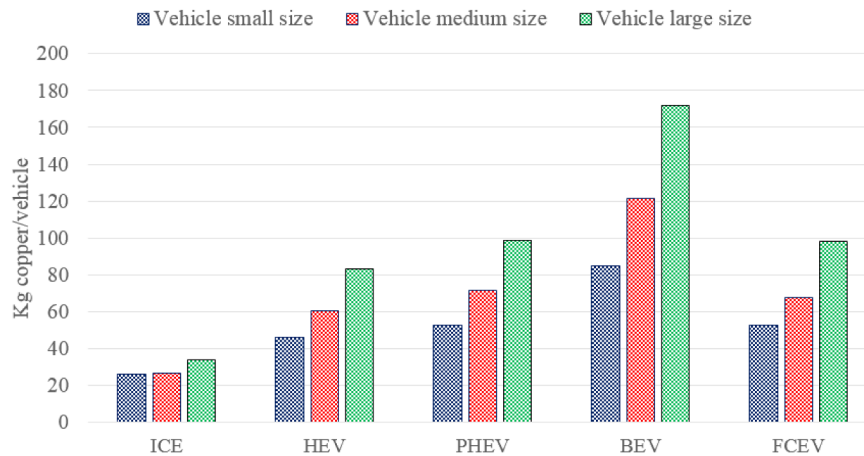
**Fig. 6.** Copper content in passenger light duty vehicles per size.
*Source*: (Burnham, 2012), **See Table 4 for more details**

**Table 4**
Copper content in road transport according to the weight (kg/vehicle).

|  |  | ICE | HEV | PHEV | BEV | FCEV |
| --- | --- | --- | --- | --- | --- | --- |
| Passenger light duty vehicles | Small | 25.9 | 46.2 | 52.8 | 84.9 | 52.8 |
|  | Medium | 26.4 | 60.6 | 71.3 | 121.3 | 67.6 |
|  | Large | 33.5 | 83.0 | 98.5 | 172.0 | 97.9 |
| Bus |  | 90.5 | 224.0 | 265.8 | 369.0 | 210.1 |
| Minibus |  | 54.9 | 136.0 | 161.4 | 224.0 | 127.5 |
| Commercial vehicles | Light | 39.1 | 96.8 | 114.9 | 200.6 | 114.2 |
|  | Medium | 57.2 | 141.5 | 167.9 | 233.1 | 132.7 |
|  | Heavy | 190.5 | 471.6 | 559.7 | 776.8 | 442.2 |
| 2-wheelers |  | 0.6 |  |  | 2.9 |  |
| 3-wheelers |  | 3.9 |  |  | 20.1 |  |

*Source:* (Burnham, 2012), ECI/CA,* Authors
*European Copper Institute/Copper Alliance, https://copperalliance.eu/ e-mobility-european-copper-market/
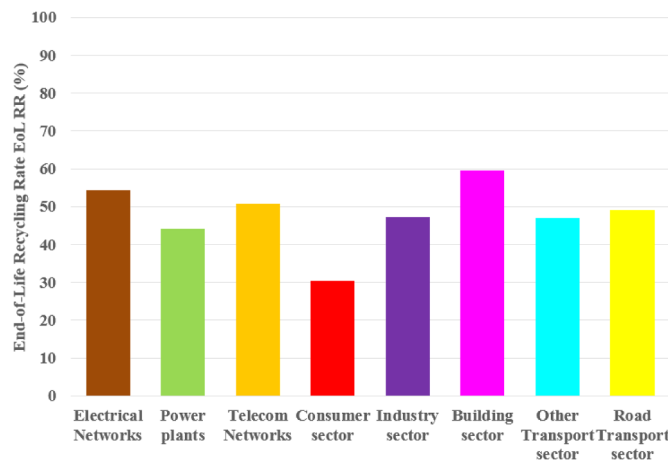


**Fig. 7.** End-of-life recycling rate (EoL-RR) by end-use sector in the TIAM-IFPEN model.
*Source*: (Glöser et al., 2013b)

scenario. On the other hand, the IEA assumed an increase of the world GDP (ppp) from around 67 912 billion US$ 2005 in 2005 to 283 500 billion US$ 2005 in 2050. Thus, the world GDP per capita (ppp) is assumed to increase from 10 430 US$ 2005 in 2005 to around 29 200 US$2005 in 2050.

### 2.3.2. Copper end-use sectors and the evolution of their demand

All end-use sectors have to be considered in the modelling exercise

to consider future copper demand, as depicted in the copper supply chain in Fig. 3 in Section 2.2.1. Two methodologies have been assumed. Firstly, the copper demands for the sectors not represented in detail technologically, Electrical and Telecom networks, Consumer, Industry sector, Building and Other Road Transport sectors, are exogenous and calculated according to the GDP per capita (ppp[13]) projection via decoupling factors. The decoupling factor series represents the sensitivity of each end-use demand to one unit change in its driver – which here is GDP per capita (GDPP). They have been derived from the analysis of the sectorial copper demands along with GDP per capita between 1975 and 2018[14] (Fig. 10), taking into account changing trends in socio-economic growth (Table 5). As mentioned before, these decoupling factors account for phenomena such as saturation (factor is then less than 1) and suppressed markets (factor is then larger than 1). Copper end-use demand for future years is projected using the equation (Eq.3):

$$D_{i,t} = D_{i,t-1} * \left( 1 + \left( \frac{GDPP_t}{GDPP_{t-1}} - 1 \right) * decoupling\_factor \right) \tag{3}$$

where $D_{i,t}$ is the copper demand for the end-use $i$ at the year $t$

Secondly, for copper demand in power plants and the road transport sector (See Appendix C for more details of their representation in the model); an endogenous technological evolution will be derived by the model while satisfying electricity needs and mobility demand respectively. TIAM-IFPEN will assess copper requirements based on new installed capacities of power plants and vehicle fleet evolution at any period.

### 2.3.3. Scenario specifications

Several scenarios have been defined in order to analyse the evolution of copper demand and assess its criticality in response to more stringent environmental constraints or sustainable behaviour requirements. We run four scenarios for copper, two climate scenarios with two different mobility shapes each:

– "Scen 4D", which is consistent with limiting the 2100 expected global average temperature increase to 4 °C above pre-industrial levels.

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[13] Purchasing Power Parity
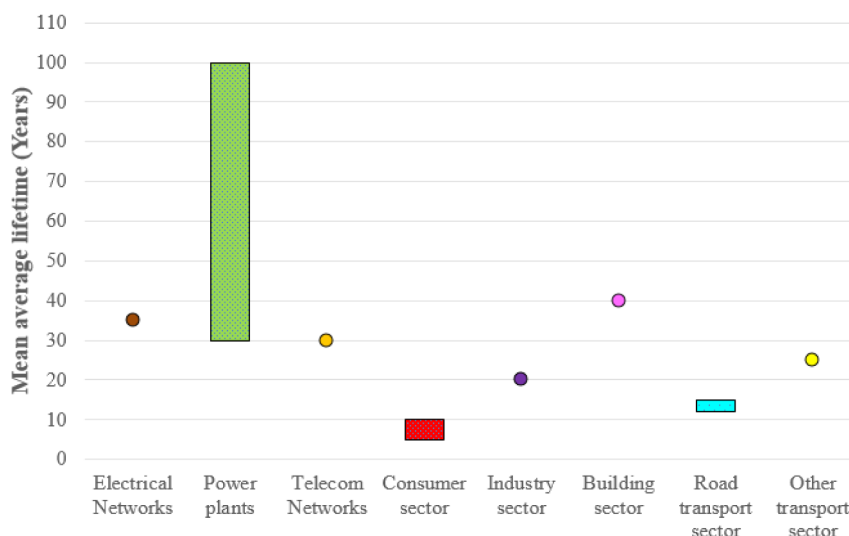[14] Annual data have been extracted and calculated from the International Copper Study Group (ICSG), Copper Council and Copper Alliance between 1975 and 2018, https://www.icsg.org/index.php/component/jdownloads/view-download/170/2965, http://www.coppercouncil.org/wp-content/uploads/2019/08/End-Use-Summary.pdf, https://copperalliance.org/trends-and-innovations/data-set/

**Fig. 8.** Mean average lifetimes by end-use sector in the TIAM-IFPEN model.
*Source*: (Glöser et al., 2013b), Authors

– "Scen 2D", which is a more ambitious scenario, corresponding to the 2100 climate objectives of limiting global warming to 2 °C.

In each climate scenario, two different future scenarios of mobility have been assumed and derived from the IEA Mobility Model (MoMo Model). In this paper, we incorporate outputs from the MoMo model as transport mobility inputs into our TIAM-IFPEN model. The two mobility scenarios for each climate scenario are (See Appendix C for more details of transport mobility evolution):

– A "BAU mobility" scenario equivalent to a continuous increase of the ownership rate and a higher car-dependency.
– A "Sustainable mobility" scenario where the idea of a sustainable mobility is assumed to underpin an integrated approach to urban land-use and transport planning and investment, and gives priority to sustainable modes of mobility such as public and non-motorized transport.
– Dealing with uncertainty in modelling is a complex endeavour that may be accomplished and in the case of TIMES-MARKAL family model, stochastic programming and parametric analysis (also known as sensitivity analysis) are two available features. By defining series of scenarios through the variation of the values of some important exogenous assumptions (sectorial demands…etc.), sensitivity analysis feature has been performed in this article. Within this approach, a sequence of instances is solved and each assuming different values of the uncertain parameters. For further research, the stochastic mode could be considered.

## 3. Results and discussions

### 3.1. Pathways to achieve the 2 °C goal

#### 3.1.1. Outlook for power sector

The fast shift to the low carbon technologies, which are very copper-intensive (see Fig. 5 in Section 2.2.1), is observed in the power sector in order to achieve the climate objectives of limiting global warming to 2 °C by 2100 (Fig. 11). The total installed capacity by 2050 in the 4 °C scenario, which is 10.5 TW, will be multiplied by around 2.5 in the 2 °C scenario. The Variable Renewable Energy sources (VREs) (wind and solar) represented around 35% by 2050 in 4 °C while it is reaching more than 69% in the 2 °C scenario in terms of installed capacity.

Fossil-based plants (coal, gas and oil) remains the main source of power production in the world in the 4 °C scenario with around 55% of

overall production while it drop to 0.8% in the more stringent scenario (2 °C scenario). In the other hand, the Variable Renewable Energy sources (VREs) (wind and solar) has the inverse trend, they represented around 21% by 2050 in the 4 °C while it is reaching more than 67% in the more stringent scenario, namely 2 °C scenario. The total power production reached in the 4 °C scenario is almost 147 EJ (around 40 800 TWh) while it is almost 246 EJ (or 68 330 TWh). As a comparison, in the WEO 2019 of the IEA (International Energy Agency, 2019a), the global power generation is expected to be 38 713 TWh in the Sustainable Development scenario[15] (SDS) by 2040 while in our model it is expected to be around 127.243 EJ, i.e. 35 345 TWh by 2040 (Fig. 11(b) and Table 6 for more details).

Achieving a high share of renewables, mainly dominated by VREs, would thus require substitute or additional plants to provide extra inertia to the system. These options might include other means of production or storage devices, or renewable energy technologies (RETs) capable of providing such inertia (see Fig. 11(a)) (Seck et al., 2020). With higher VREs penetration by the 2050 horizon, nuclear energy combined with more biomass or hydro to ensure the reliability of the grid with a minimum share of dispatchable electricity in the grid. Wind is expected to be the dominant energy as observed in Fig. 11(b). The system begins to introduce flexible options, such as storage devices from 2040 onwards in the 2 °C scenario, despite the fact that this introduction of storage is quite low, which is more or less visible in the graphs.

#### 3.1.2. Outlook for road transport sector

The high level of the transport electrification achieved in the 2 °C scenario will have an impact on the copper demand (Fig. 12). Indeed, according to literature (Vidal, 2018b), electric vehicles contain two to more than five times more copper than the conventional vehicles according to their size (Fig. 6). 50% of the global fleet would be electric vehicles in the 2 °C scenario while it is only 21% by 2050. We should pinpoint that around 1/3 of the world fleet are 2/3-wheelers (mostly in China and India) and around 50% of the electric fleet. Therefore, EV fleet is mostly located in Asian countries (China, India and Other developing countries in Asia) due to the large presence of these 2/3-

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[15] The Sustainable Development Scenario is constructed on the basis of limiting the temperature rise to below 1.8 °C with a 66% probability without the implied reliance on global net-negative CO2 emissions, or 1.65 °C with a 50% probability (International Energy Agency, 2019a).
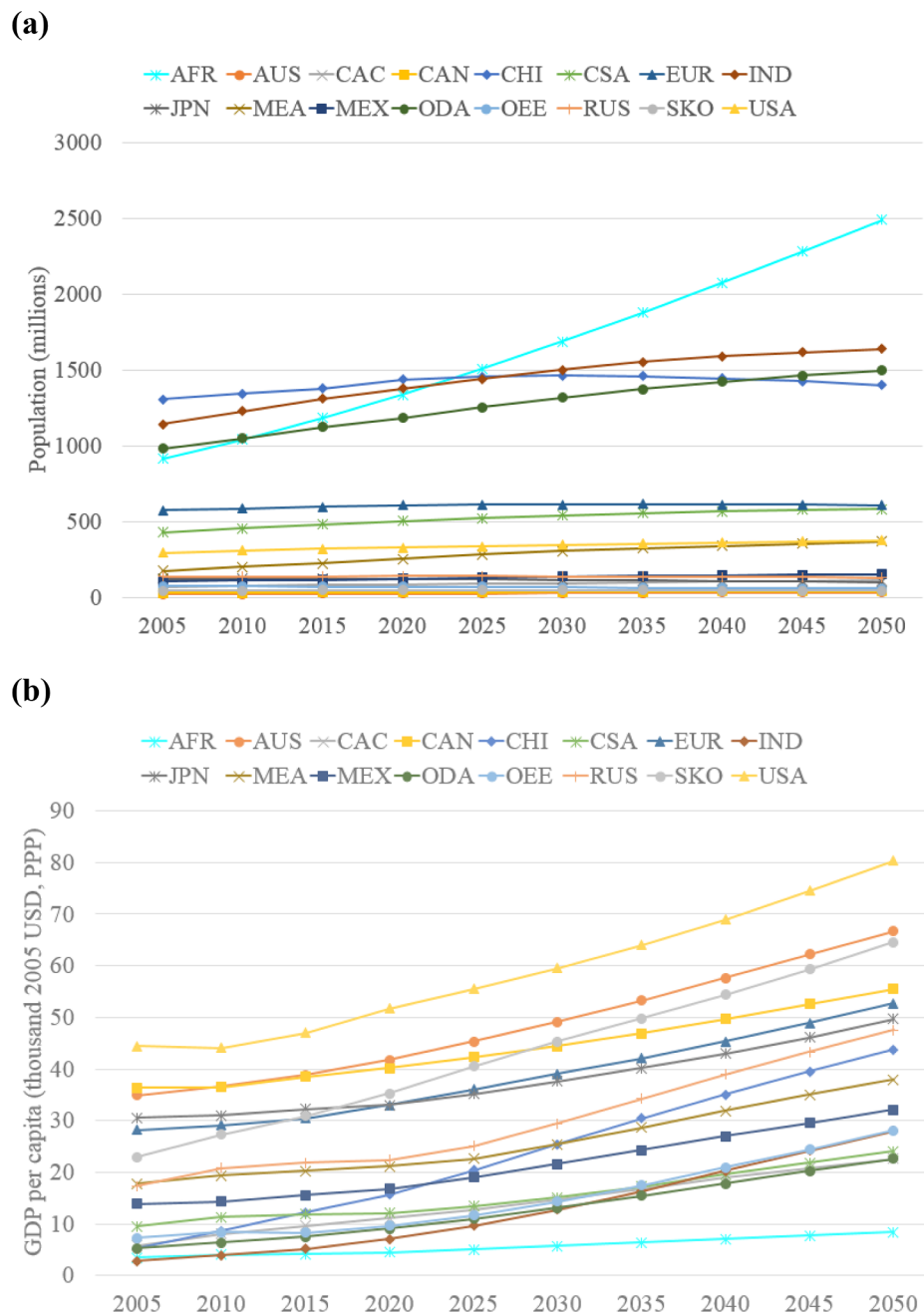
**(a)**



**(b)**



**Fig. 9.** (a) Evolution of population, (b) Evolution of the GDP per capita.
*Source*: International Energy Agency (IEA), (United Nations (UN), Department of Economic and Social Affairs, Population Division 2019)

wheelers.

With a sustainable mobility, the worldwide fleet achieves 3.5 and 3.4 billion vehicles in the 4 °C and the 2 °C scenarios by 2050, respectively, while it is more than 4.3 and 4.1 billion in a "Business-As-Usual" mobility. The impact of the mobility shift will allow a reduction of around 700–800 million vehicle due to the reduction of the mobility activity with the development of sustainable modes of mobility such as public and non-motorized transport.

The world fleet is dominated by the internal combustion engine (ICE) vehicles between 2005 and 2050 (except in the scenario 2 °C from 2040 onward) (Fig. 12).

According to Fig. 13(a), the global fleet of EV (two and three-wheelers excluded) should reach between 450 and 500 million units by 2050 in the 4 °C scenarios, while it could be as high as 785–900 million units in the 2° scenarios. When considering passenger light-duty

vehicles (PLDVs: small, medium and large cars) alone, they should reach 390 and 435 million units in circulation by 2050 in the 4 °C scenarios with the sustainable and BAU mobility, respectively, while it would be more than 675 and less than 800 million in Sustainable mobility and BAU hypothesis in the 2 °C scenario (Fig. 13(b)).

Our model gives a global EV fleet (2/3-wheelers excluded) between 7.798 and 7.821 million vehicles in 2020. The existing EV worldwide fleet has been counted to be approximately 6.655 million vehicles worldwide in 2019 according to MarkLines. Therefore, it could be considered that our results are in fair agreement if considering that the estimated new EV sales would certainly decrease after a 4% decline in sales in 2019, following the slowdown in global economic growth and the implementation of new regulations in Europe and China due to the Covid-19 pandemic. Analysing these graphs, we could acknowledge that our forecasts in the 4 °C and 2 °C scenarios with the "Business-As-
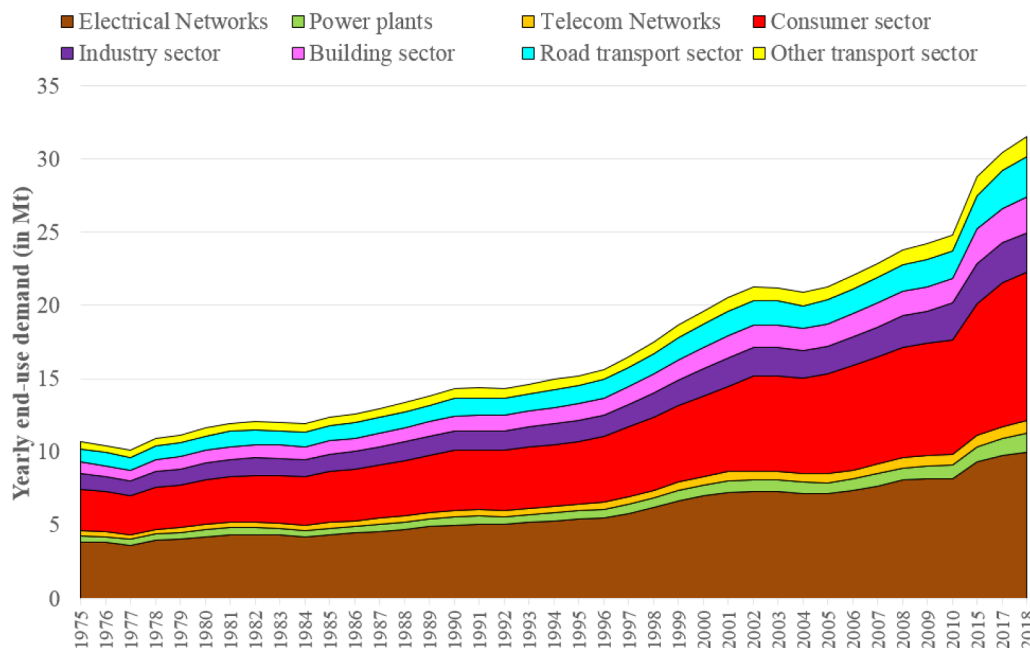
**Fig. 10.** Global copper demand by end-uses.
*Source*: ICSG, Copper Council, Copper Alliance

**Table 5**
Estimated decoupling factors.

|  | Electrical Networks | Telecom Networks | Consumer sector | Industry sector | Building sector | Other transport sector |
|---|---|---|---|---|---|---|
| Estimated sensitivity to GDP per capita | 1.21 | 1.21 | 1.65 | 0.95 | 1.67 | 1.17 |

Usual" mobility, 110 and 180 million units by 2030, respectively, are similar in scope to the IEA's forecasts in the Global EV Outlook (GEVO) 2019, which estimates the number of EV at between 130 and 250 million by 2030 in the New Policies Scenario[16] and EV30@30 scenario[17] (Table 7) (International Energy Agency, 2019b).

### 3.2. The impact of the energy transition on global copper demand

We aim to quantify the impact of the energy transition on copper resources. We therefore compare the remaining copper resources in 2050 under the most stringent 4 °C and 2 °C climate scenarios, i.e. with the "Business-As-Usual" mobility. Both scenarios assume that resources are available for copper mining at current cost. This rather optimistic assumption does not impose any delay in the conversion of resources into reserves. This simplifies the modelling and allows us to avoid any arbitrary assumptions about the timing of future copper reserves development. In addition, assuming that the copper contained in resources is available, the total amount of copper required can be quantified based on our scenarios, as described above. Figs. 14 and 15 compare total cumulative copper extracted from the mines and the total

cumulative copper consumed, respectively, between 2010 and 2050 with the global identified copper resources in 2010 (Mudd et al., 2013), and the global identified copper resources in 2010 plus the estimated undiscovered resources in 2013 (USGS 2014) under climate scenarios. According to the graphs, the two leftmost bars represent cumulative global extraction/or consumption of copper in the 4 °C and 2 °C scenarios, and its distribution amongst the producing/or consuming regions. The two rightmost bars depict the global identified copper resources in 2010, and the global identified copper resources plus the estimated undiscovered copper resources at 90% chance assessed in 2013. The global reserves in 2019 according to the USGS are represented by the horizontal red line in both graphs. On the right axis, we have defined an indicator for a dynamic assessment of copper criticality either the copper extraction or the copper consumption as a reference. This indicator, which could be also called the safety margin, is calculated as the ratio of cumulative copper extracted/ or consumed to the resources.

According to the Fig. 14, between 2010 and 2050, 78.3% and 89.4% of the global identified copper resources will be extracted in the 4 °C and 2 °C scenarios, respectively. These latter criticalities in copper mining will fall to 47% and 53.7%, respectively, if the undiscovered copper resources estimated at a 90% chance, as assumed by the USGS, are also available. In comparison, the current copper reserves in 2019, which is 870 Mt, would not be sufficient after 2035 or 2040 to satisfy the copper extraction evolution in average in the 2 °C and 4 °C scenarios, respectively. However, it should be noted that our cumulative primary copper demand is around 1600–1900 Mt between 2015 and 2050 with a recycling rate of 45% while it is estimated around 800–1000 Mt in Schipper et al. (2018) for the SSP1, SSP2 and SSP5 scenarios, with each 70% and 90% recycling rates. In addition, they reminded that recycling rates of 70 and 90% are extremely speculative, they are used to represent an ideal situation regarding recycling. Reaching 70–90% recycling rate of copper would require significant

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[16] The New Policies Scenario has been renamed The Stated Policies Scenario, by contrast, incorporates today's policy intentions and targets to underline that it considers only specific policy initiatives that have already been announced. The aim is to hold up a mirror to the plans of today's policy makers and illustrate their consequences, not to guess how these policy preferences may change in the future. This trajectory is consistent with limiting the temperature increase to below 2.7 °C above pre-industrial averages with a 50% probability (or below 3.2 °C with 66% probability) (International Energy Agency 2019a).

[17] The EV30@30 Scenario takes into account the pledges of the Electric Vehicle Initiative's EV30@30 Campaign to reach a 30% market share for EVs in all modes except two-wheelers by 2030 (International Energy Agency IEA, 2019).
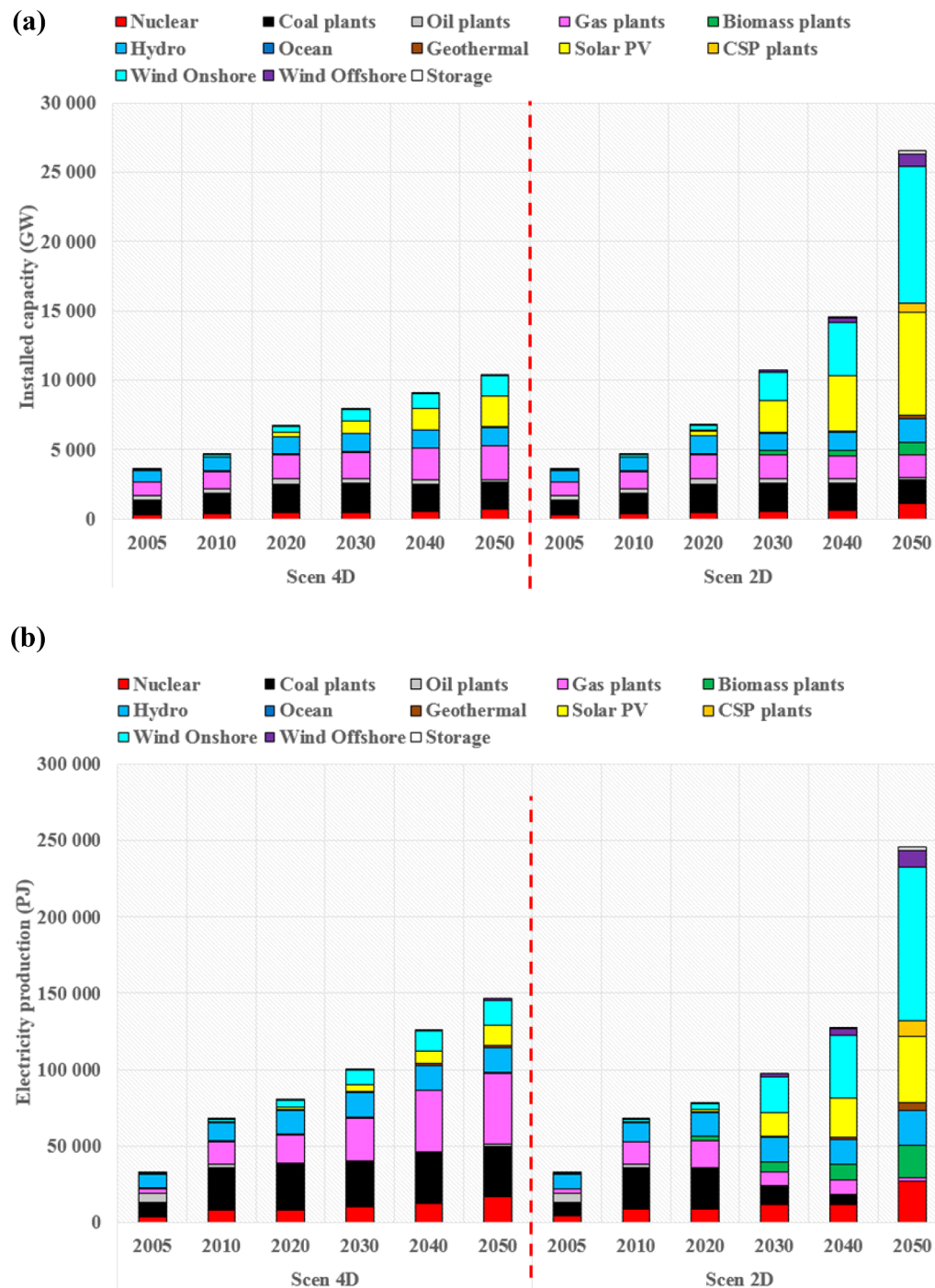
**Fig. 11.** (a) Evolution of World power installed capacity with climate constraints (b) Evolution of the world power production with climate constraints.
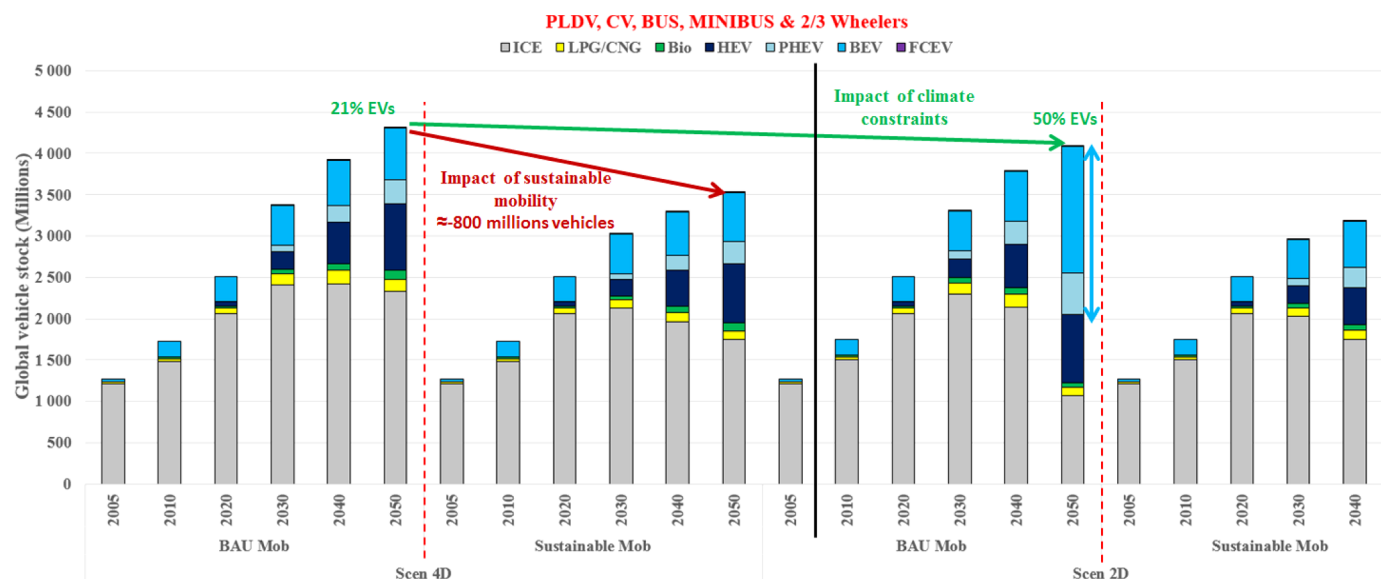
**Table 6**

Comparison of our modelling results in electricity generation (in TWh) in 2040 with recent literature.[*],[**]

| | Our results | | IEA WEO 2019 (International Energy Agency, 2019a) | | |
|---|---|---|---|---|---|
| | 4 °C Scenario | 2 °C Scenario | Current Policies scenario | Stated Policies scenario | Sustainable Development scenario |
| 2040 | 35 115 | 35 345 | 42 824 | 41 373 | 38 713 |

[*]The Current Policies scenario shows what happens if the world continues along its present path, without any additional changes in policy, The Stated Policies Scenario previously named New Policies scenario, by contrast, incorporates today's policy intentions and targets. And the Sustainable Development Scenario maps out a way to meet sustainable energy goals in full, requiring rapid and widespread changes across all parts of the energy system.

[**]This scenario is consistent with limiting the temperature increase to below 2.7 °C above pre-industrial averages with a 50% probability (or below 3.2 °C with 66% probability).

**PLDV, CV, BUS, MINIBUS & 2/3 Wheelers**

ICE: Internal combustion engine; HEV: Full hybrid vehicle; PHEV: Plug-in hybrid vehicle; BEV: Battery-powered
electric vehicle; FCEV: Fuel cell electric vehicle; EVs=BEVs+PHEVs+FCEVs

**Fig. 12.** Evolution of the global vehicle stock between 2005 and 2050.

**Table 7**
Comparison of our modelling results in future global EV stock in 2030 with
recent literature.

|      | Our results | | IEA GEVO 2019 (International Energy Agency, 2019b) | |
| --- | --- | --- | --- | --- |
|      | 4 °C Scenario | 2 °C Scenario | Stated Policies scenario | EV30@30 scenario |
| 2030 | 110 million | 180 million | 130 million | 250 million |

changes in the way products are designed, and would be difficulty to
acquire in short term. Halada et al. (2008) have obtained cumulative
primary copper production between 1500 and 1900 Mt depending on
the scenario. These conclusions from this recent scientific literature are
found to be in agreement with our primary copper evolution by 2050 in
Fig. 14 (Table 8)[18].

Considering copper consumption as a reference in the definition of
criticality, the results in Fig. 15, combined with the ones in Fig. 14,
show the importance of the secondary production in the copper de-
mand. Indeed, observing Fig. 15, it can be pinpointed that without any
secondary production, the total cumulative copper consumption be-
tween 2010 and 2050 would have been 119.2% and 130.7% of the
wold's known resources in the 4 °C and 2 °C scenarios, respectively.

These two graphs also highlight the regions which are the most
producing, consuming ones or both. China, Western Europe, Japan and
United States of America represent almost 65% of the total cumulative
copper consumption (averaging 31%, 14%, 13% and 6%, respectively)
between 2010 and 2050 in the 4 °C or 2 °C scenarios. While around 60%

of the total cumulative copper mined between 2010 and 2050 was done
in only four regions: Central and South America, China, Other devel-
oping Asian countries and Western Europe (averaging 20%, 18%, 13%
and 9%, respectively) in the 4 °C and 2 °C scenarios.

China and Western Europe, as can be observed in Fig. 16, extract
more than the totality of their identified domestic resources in both
climate scenarios. Taking into account USGS estimates of undiscovered
resources would increase China's copper resources by a factor of 4.48
from their 2010 level. Assuming these resources become exploitable by
2050, we can see that the projected growth of the Chinese economy and
its copper needs are pushing the country to consume all its resources
and to import part of the copper it uses.

Three other regions are also represented in Fig. 16: Africa, Central &
South America and the United States of America (USA). They share the
characteristic of having abundant copper resources, allowing them to
meet domestic demand in both climate scenarios while exporting pri-
mary copper. As expected, Central & South America will obtain an
additional rent from resource extraction in the 4 °C and 2 °C scenario.
This is the geographical area that shows the greatest difference in the
two climate scenarios in terms of copper quantities extracted and do-
mestic copper consumption (Figs. 14 and 15). However, the Latin
America monopoly may face a competitive fringe of smaller copper
producers. Indeed, according to our results, Africa, Central Asia & the
Caucasus, Canada, Mexico, Russia, the USA and the Other Developing
Asian countries are regions with enough copper resources to meet do-
mestic demand and export to other regions in both climate scenarios.

The yearly copper consumption increases with the growing GDP per
capita and will vary from around 27 Mt in 2015 to around 86 Mt and
102 Mt in 2050 in the 4 °C and 2 °C scenarios, respectively (Fig. 17(a)).
These values combined with the evolution of the world population
given by the UN population, the average consumption of copper per
inhabitant per year is calculated to increase from 3.6 kg/cap/yr in 2015
for a GDP per capita (ppp) of 13 102.7 US$ 2005 to 8.9 and 10.5 kg/
cap/yr in 2050 for a GDP per capita of around 29 200 US$2005 in the
4 °C and 2 °C scenarios, respectively. According to our results, our
global copper demand in 2050 is therefore about double or more the
value found by Elshkaki et al. (2016) of 45 Mt and the same trend is
observed on the copper intensity per capita in 2050. However,
Halada et al. (2008) estimated the copper consumption of only 10
countries (so-called BRICs (Brazil, Russia, India, China) and the original

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[18] These are the four "storylines" of the UNEP GEO-4 foundational scenarios:
Market First (MF). A market-driven world in which demographic, economic,
environmental, and technological trends unfold without major surprise relative
to currently unfolding trends. Policy First (PF). A world in which strong actions
are undertaken by governments in an attempt to reach specific social and en-
vironmental goals, especially as pertains to renewable energy.Security First
(SF). A world of great disparities where inequality and conflict prevail, brought
about by socio-economic an environmental stresses.Equitability First (EF). A
world in which a new development paradigm emerges in response to the
challenge of sustainability, supported by new, more equitable values and in-
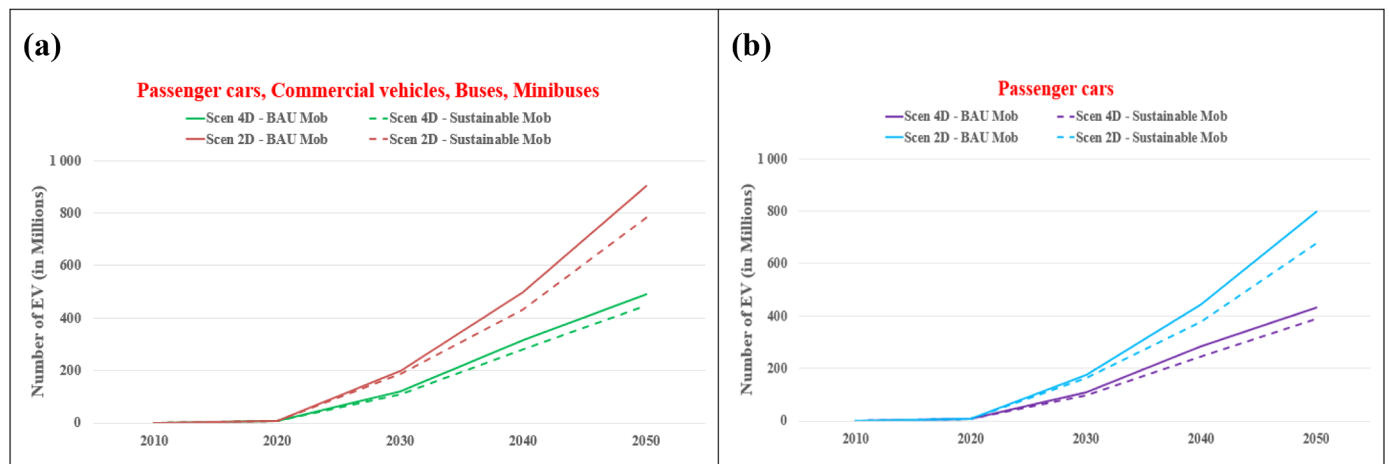stitutions.

**Fig. 13.** (a) Evolution of the global electric vehicle fleet (b) Evolution of the electric vehicles in passenger light-duty vehicles.
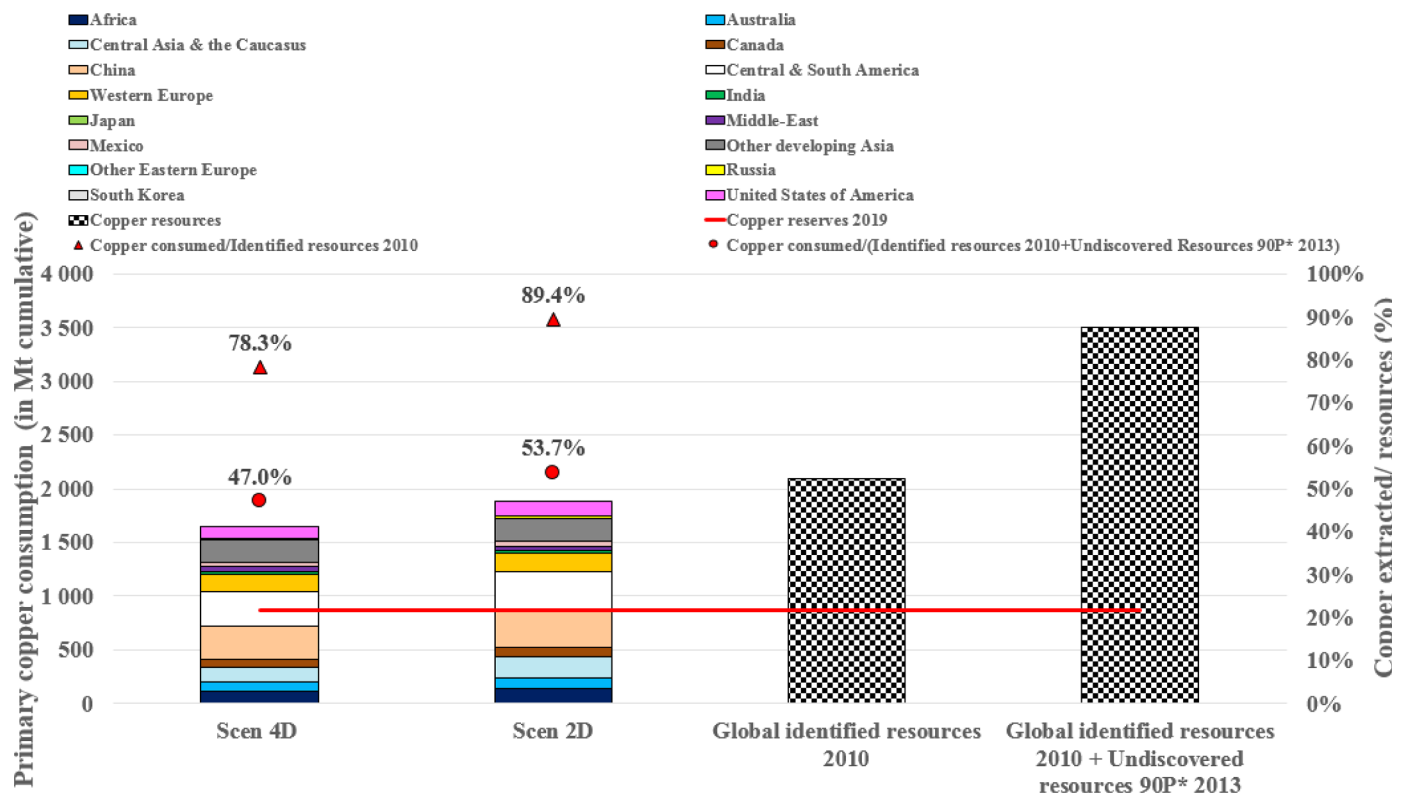


**Fig. 14.** Comparison between cumulative primary copper production through to 2050 under two climate scenarios and the identified and undiscovered copper worldwide in 2013.
***Source***: USGS, Authors' results
"90P" indicates a 90-percent chance of at least the amount shown, with other percentiles similarly defined

G6 countries of Japan, USA, UK, France, Germany, and Italy) and they found around 45 Mt by 2050. We found our global copper demand to be also in line with the values from top-down method (regressions) or bottom-up stock dynamics method in the three scenarios SSP1, SSP2 and SSP5 estimated by Schipper et al. (2018) by 2050 (Table 9).

These results pinpoint the fact that the demand for copper will exceed the current reserves as well as ruining almost the global identified resources by 2050. The development of the copper recycling sector would play an important role in the future. It may exist a risk that this geological criticality could hamper the diffusion of low-carbon technologies. To this extent, two policy options have been assessed in the next section.

### 3.3. The impact of public policies aimed at reducing world copper demand

#### 3.3.1. The regionalized impact of sectorial copper recycling capacities

Our results show that the energy transition will require the development of new copper reserves, highlighting the importance of recycling as a key lever for a more efficient use of copper resources. It is relevant to analyse the evolution of recycling over the coming decades, as it illustrates the mechanisms that can lead to secondary (recycled) copper decreasing as a proportion of total copper consumption over time. The growth rate of copper demand and its sectorial composition are two crucial elements in understanding the dynamics of recycling. They jointly determine both the composition of copper scrap, which, depending on its source, will be more or less costly to recycle in the
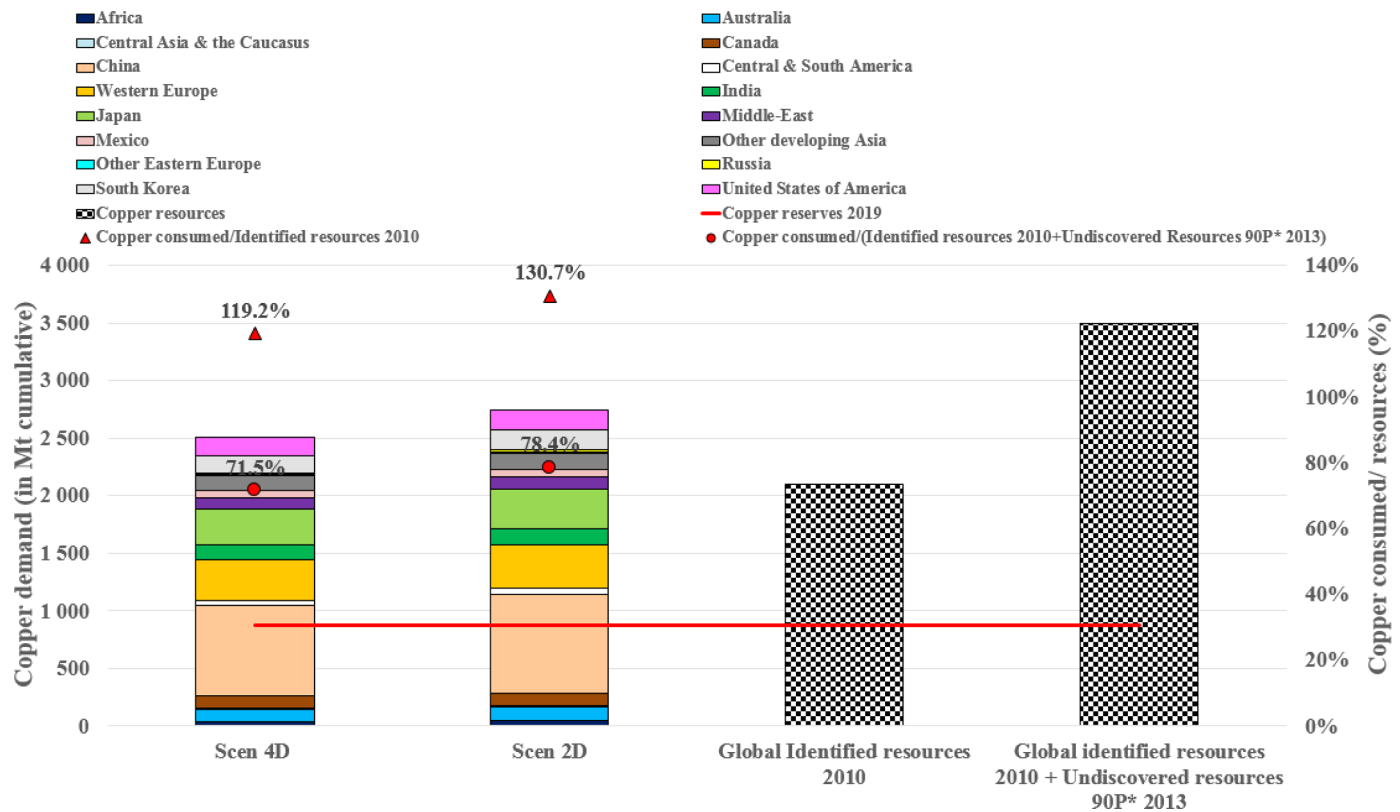
**Fig. 15.** Comparison between cumulative copper consumption through to 2050 under two climate scenarios and the identified and undiscovered copper worldwide in 2014.

*Source*: USGS, Authors' results

"90P" indicates a 90-percent chance of at least the amount shown, with other percentiles similarly defined

**Table 8**

Comparison of our modelling results in cumulative primary copper demand between 2015 and 2050 with recent literature.*

| | Our results | | Schipper et al. (2018) | Elshkaki et al. (2016) |
|---|---|---|---|---|
| | 4 °C scenario | 2 °C scenario | SSP1, SSP2 and SSP5 scenarios | EF, SF, PF and MF scenarios |
| Cumulative primary copper demand | 1600 Mt | 1900 Mt | 800 – 1000 Mt | 1500 – 1900 Mt |
| Average recycling rate considered | 45% | | 70% and 90% for each scenario | 45% |

*These are the four "storylines" of the UNEP GEO-4 foundational scenarios: Market First (MF). A market-driven world in which demographic, economic, environmental, and technological trends unfold without major surprise relative to currently unfolding trends. Policy First (PF). A world in which strong actions are undertaken by governments in an attempt to reach specific social and environmental goals, especially as pertains to renewable energy.Security First (SF). A world of great disparities where inequality and conflict prevail, brought about by socio-economic an environmental stresses.Equitability First (EF). A world in which a new development paradigm emerges in response to the challenge of sustainability, supported by new, more equitable values and institutions.

future, and the rate at which copper is immobilized in applications with varying lifetimes. A country that experiences strong growth in copper demand to supply the consumption of dispersive uses therefore runs the risk of seeing the share of its copper demand covered through secondary production decrease over time.

This phenomenon has been quantified by our model and is represented in Fig. 18. It shows the evolution of copper consumption in the 2 °C scenario over five decades for several major consumer regions. A distinction is made between the two sources of copper consumed: primary copper, and secondary copper from recycling. The share of recycled copper in consumption is expressed as a percentage on the data labels.

Although recycling practices are calibrated on historical data (Glöser et al., 2013b), the share of secondary copper in total copper demand does not remain stable over time because the dynamic speed of the copper demand and the available scrap copper stock used for recycling are different. This is particularly important for countries or regions where strong economic growth is expected, such as Africa,

India, and to a lesser extent China. Secondary production accounts for the largest share of domestic consumption in these countries in 2020. Over time, the acceleration in consumption outweighs the rate of accumulation of copper scrap available for recycling and demand for copper is increasingly met through primary production. This result demonstrates the importance for countries experiencing strong economic growth of developing an efficient upstream copper recycling sector to reduce import dependency. Europe, Japan, USA and South Korea, due to their moderate expected economic growth, can maintain relatively stable secondary production share over time after 2030.

*3.3.2. The regionalized development of a sustainable mobility in road transport sector*

The road transport sector is crucial for the future evolution of copper consumption, as low-carbon vehicles are more copper-intensive than conventional ones. This sector is a major emitter of greenhouse gases. The evolution of sectorial consumption is depicted, all regions combined, in Fig. 19, in a 2 °C scenario where road transport mobility is
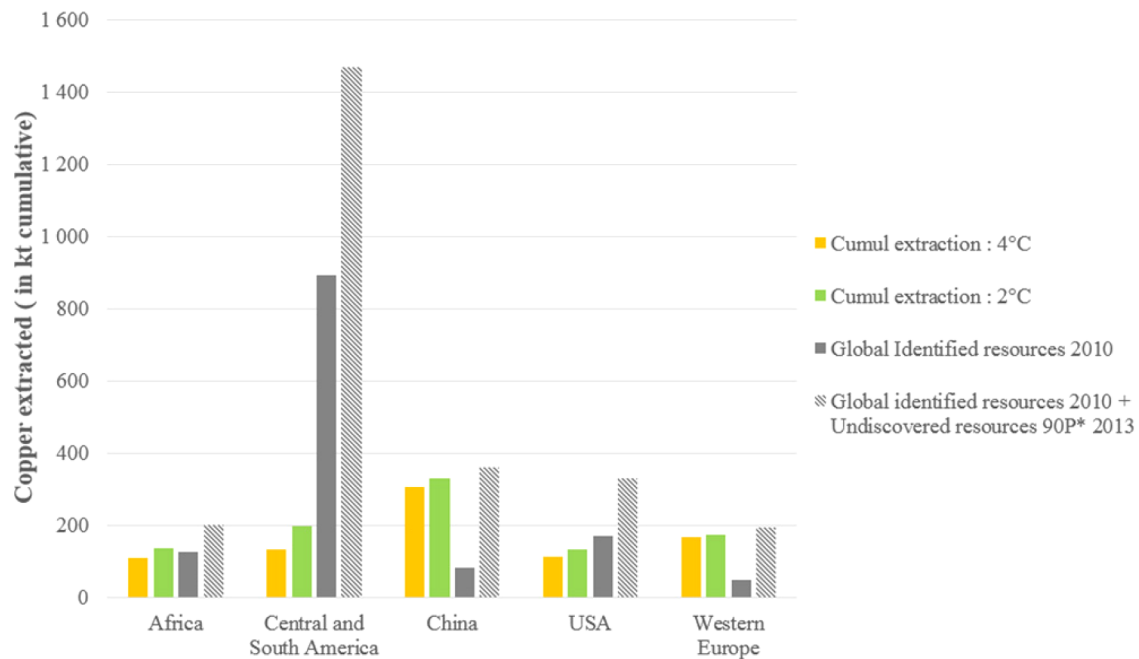
**Fig. 16.** Cumulative domestic extractions over the 2010–2050 period in the two climate scenarios and domestic copper resources (in cumulative kt).
*Source*: **USGS, Authors' results**
"90P" indicates a 90-percent chance of at least the amount shown, with other percentiles similarly defined
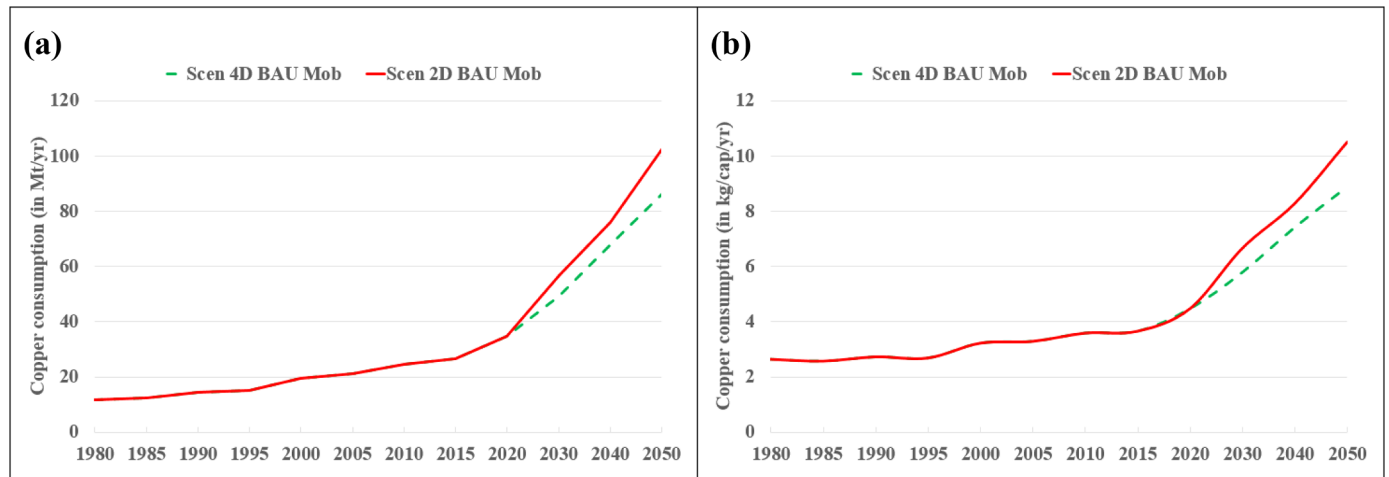


**Fig. 17.** (a) Evolution of the yearly copper consumption (b) Evolution of yearly copper consumption per capita.

considered to evolve. In this graph, we represented the results of the 2 °C scenario within a "Business-As-Usual" and 3Sustainable" mobility.

The dotted line represents the evolution of total copper consumption under a sustainable transport mobility hypothesis, as detailed in §2.3.3. The area between this dotted line and the upper limit of the copper consumption of the road transport sector (red arrow) represents the copper consumption savings achieved through a more sustainable transport mobility. The results in Fig. 19 indicate that copper consumption will be driven mainly by three sectors: road transport (green arrow), consumer goods and networks. During the period 2040–2050, the impact of the power generation sector increases due to the fast roll-out of RETs to limit the global temperate rise to 2 °C as already seen in Fig. 11. Energy transport and telecommunication networks enable the deployment of smart grids and make energy demand more flexible. The consumer goods sector is a highly diverse group of goods. Public policies and market forces will help regulate consumption more effectively than rationing, which obviously has practical and political limits. The road transport sector thus triggers copper savings: the

**Table 9**
Comparison of our modelling results in global copper demand in 2050 with recent literature.

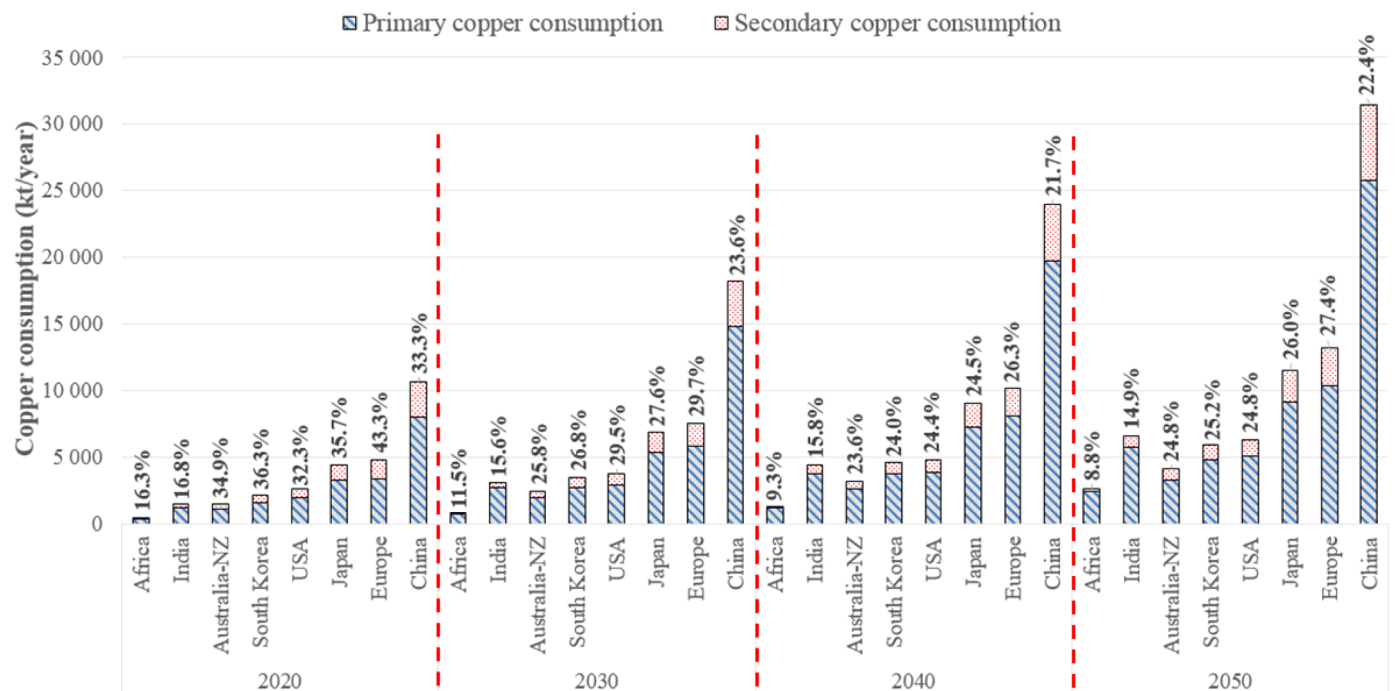| | Our results | | Vidal et al. (2019) | Schipper et al. (2018) | Elshkaki et al. (2016) | Halada et al. (2008) |
|---|---|---|---|---|---|---|
| | 4 °C scenario | 2 °C scenario | Main scenario | SSP1, SSP2 and SSP5 scenarios | EF, SF, PF and MF scenarios | Scenario for only 10 countries (BRICS and G6) |
| Global copper demand in 2050 | 86 Mt | 102 Mt | 45 Mt | 70 −125 Mt | 40 – 70 Mt | 45 Mt |

**Fig. 18.** Evolution and distribution of domestic copper consumption for major consumers (2006–2050) (in kt copper).
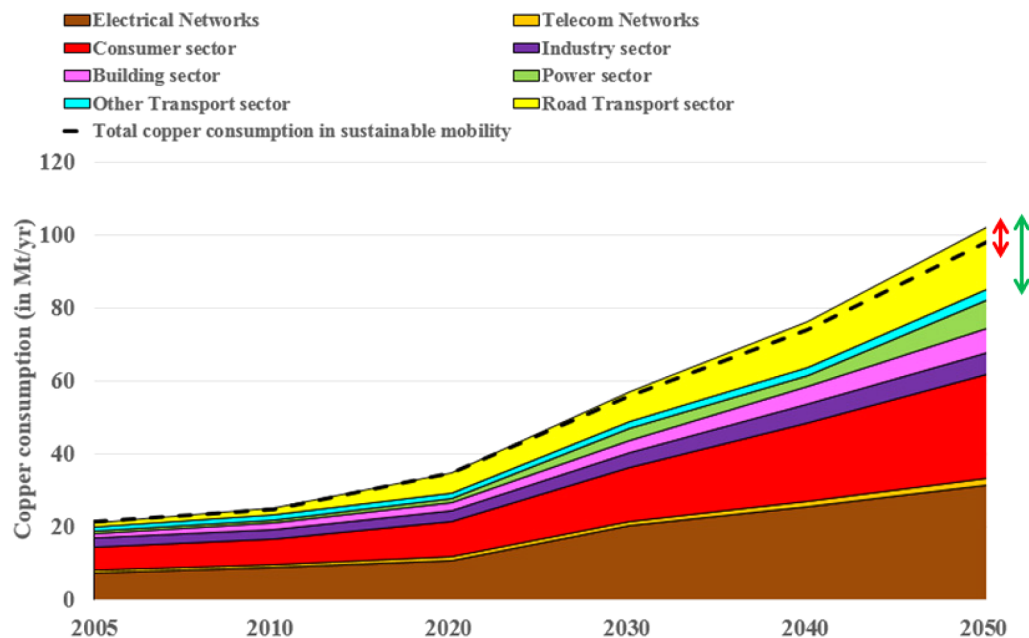


**Fig. 19.** Evolution of the copper consumption in the 2 °C scenario: an assessment of the impact of the transport mobility shift.

implementation of sustainable mobility policies would reduce the ecological impacts of mobility while limiting use of copper resources.

Here, we focus on the consequences of more sustainable mobility on copper consumption. It varies significantly across the model's regions. To account for these differences, the share of reduction in total copper consumption over the period 2010–2050 attributable to a sustainable transport mobility in a 2 °C climate scenario is represented in Fig. 20.

For most countries, these reduce cumulative copper consumption over the period 2010–2050 are between 2% to 20%. Countries and regions where sustainable mobility has only a small effect on copper consumption are Canada, Western Europe, South Korea, Australia-NZ, and Japan. This results from the combined effects of transport policies,

socio-economic development and urban population density evolution. Indeed, most OECD worldwide have constantly adjusted their transport policies over time through an integrated approach to land use and transport planning, transport pricing (congestion pricing schemes, road tolls) and parking restrictions to challenge car attractiveness, while providing alternative modes of transport (Hache et al., 2019a). These measures, combined with these (OECD) countries' constant urban population density through to 2050, have helped reduce car dependency (including, amongst other indicators, a reduced vehicle ownership rate[19]), therefore keeping vehicle stocks constant or slightly down,

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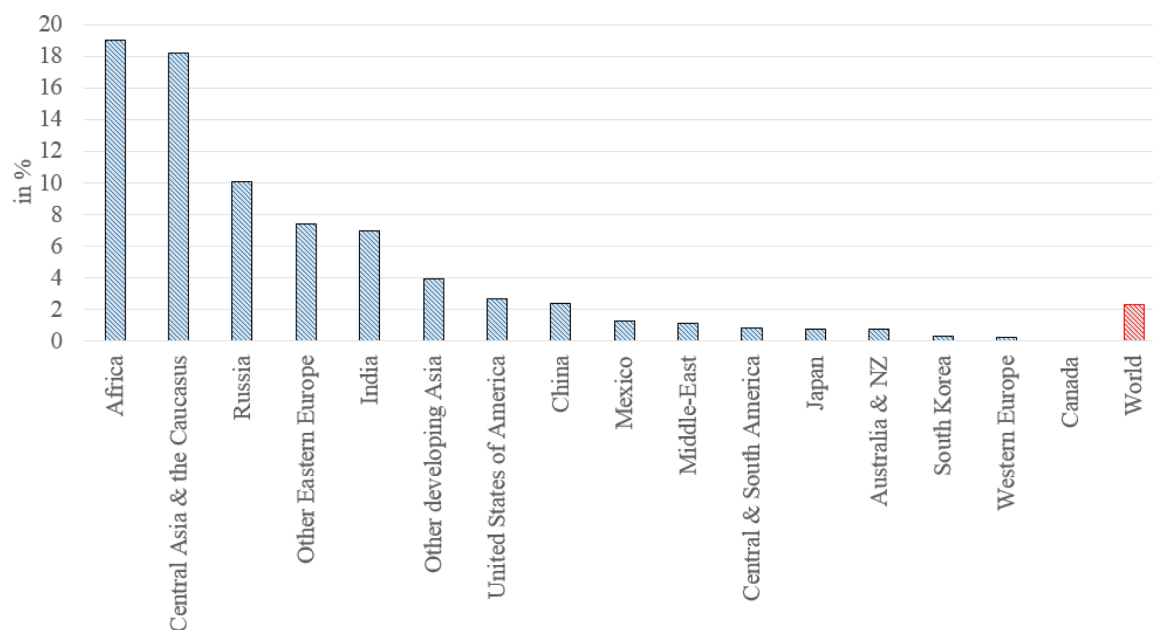[19] The number of vehicles per 1000 inhabitants.

**Fig. 20.** Share of copper consumption avoided through a sustainable mobility scenario (in%), 2010–2050.

through switches to more sustainable modes of transport. The case of the United States of America and Canada should be noticed here due to their high car dependency. As expected in Canada, the development of modes of mobility such as public and non-motorized transport will be more difficult due to the country configuration while in the USA this transport shift will have higher impact than in other OECD countries. For other regions, mostly non-OECD, the contrary is observed in the current transport structure. In the case of a BAU mobility scenario, they are likely to evolve towards a very high dependence on cars due to a lack of efficient public transport infrastructure. This explains the high share of primary copper consumption saved in these countries under a sustainable mobility scenario. The case of China, India and Other Developing Asian countries (ODA) should be highlighted due to the predominance of 2/3-wheelers. In a sustainable mobility scenario, a slight switch from cars to this mode of transport will also be observed. In the case of China and India for example, due to their scale and combined with more public and non-motorized mobility, significant quantities of copper can be saved. At the global level, if all regions implement policies aimed at achieving more sustainable mobility, overall cumulative copper consumption could be reduced by 2.3%.

## 4. Conclusion

We assess the criticality risk for copper in the context of the energy transition. For the first time, an energy system optimization model has been developed to integrate both a detailed representation of the copper supply chain and the copper content of the technologies available in two major sectors of the energy transition: power and transport.

- The first interest of our modelling approach is to link the diffusion of low-carbon technologies to copper resources. The technological mix and its evolution therefore interact directly with the rate of copper-resource depletion. Our scenarios demonstrate that 78.3% of the copper resources known in 2010 will have to be extracted from the ground between 2010 and 2050 in a 4 °C scenario, and 89.4% in a 2 °C scenario. China and Europe are set to become highly dependant on external sources, and Central and South America will provide a significant portion of copper production to meet the additional demand resulting from the energy transition although other regions such as Africa, Central Asia & the Caucasus, Canada, Mexico, Russia, the USA and the Other Developing Asian countries with enough

copper resources to meet domestic demand and export to other regions in both climate scenarios. When considering the final copper consumption, the global identified resources will have not be sufficient if recycling would have not been considered. Indeed, the cumulative final copper consumption between 2010 and 2050 is found to be at around 119.2% and 130.7% of the global copper resources known in 2010 for the 4 °C and 2 °C scenarios, respectively. These results show that the rate of increase in world copper consumption is likely to put pressure on existing copper production capacity. In this context, there rapid increase in copper consumption should be followed by the development of copper recycling sectors or demand management policies in order to not hamper the energy transition process. Our results therefore underline the importance of policies to smooth future demand trends.

- Two public policy options have also been considered in these analyses in order to reduce the rate of growth of copper demand: strengthening recycling capacities and accelerating sustainable mobility policies.
- With regard to recycling, our results highlight the importance of strengthening copper recycling channels now, particularly in countries with strong growth prospects. The rate of deployment of copper-intensive and long-life technologies is the highest in these countries. This changes the sectorial composition of the copper scrap flow available for recycling each year and, ultimately, can reduce the share of secondary copper in total copper consumption.
- Another option could be to implement a sustainable transport mobility policy in order to reduce demand for low-carbon and copper-intensive vehicles. This could be supported by strong transport policies aimed at reducing car dependency and promoting the use of alternative modes of transport (walking, cycling, shared mobility, and public transport). While copper savings may seem minor at global level, this strategy may be important for some countries. Indeed, several of the model's regions, including Africa, Central Asia and the Caucasus, Russia, Other Eastern European countries, India, and Other Developing Asian countries could reduce their cumulative consumption of copper consumption by more than 5% over the period 2010–2050.
- While our scenarios show the importance of the copper resources held by the region Central and South America (Chile and Peru). This region does not eliminate uncertainty about the ability and willingness of its producing countries to continue increasing copper

production capacities, particularly due to environmental externalities (local pollution and water resource availability) caused by the exploitation of the ore produced.

Other perspectives of our global model for further research on copper, in particular, would be to analyse the impact of an increasing recycling rate, while also in general, it would be relevant to implement and analyse the impact of water resource availability on some major raw material production, therefore on the energy transition. The integration of other strategic materials such as cobalt, nickel and rare-earth metals (neodymium, terbium, lanthanum amongst others) would be very valuable with the increasing deployment of Electric Vehicles (EVs) and Renewable Energy Technologies (RETs). This new global energy model could be very useful as a decision-making tool to better understand investments in low-carbon technologies based on future raw material resource constraints for better sectorial assessment.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgement

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.105072.

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